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The Western Andes and their Relation to the Tertiary Coast-Belt, Ecuador.

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(PLATES XVIII–XX.)

THE object of the present paper is to give some geological description of the western range of the Andes, and the Tertiary formations which are developed along the Pacific coast. References are also made to the plutonic and other types of igneous rocks which are known to occur and have not been described hitherto. During the past four years the author has made a complete traverse of the Andes in Ecuador, viz. from Babahoya to Guaranda, thence to Riobamba and Baños, including the entrance to the Oriente.

Certain rock types occurring in the latter region have been already described (4) [1] : it remains, therefore, to give some general idea both of the geological formations and the structure of the same, which are found in the extensive region farther to the west.

At the outset it should be clearly understood that the observations put forward must be considered in a general sense only, as most of the rocks constituting the great mountain range known as the Western Cordillera of the Andes are covered largely by an overburden of comparatively recent volcanic detritus with lavas, and it is only in the deeper river gorges or, curiously enough, in the highest ridges of the main range, that true outcrops without an excessive covering of more recent material can be examined.

As has been dealt with more fully in previous papers by the writer the coast-belt proper consists essentially of Tertiary formations into which certain hypabyssal types of igneous rock have been intruded. Occasional plutonic forms also occur in association with these sediments, e.g. at Pascuales (1). Towards the east of the Tertiary belt, however, a great physiographical contrast is at once apparent and, with the exception of small isolated

[1] Figures in parentheses refer to References at end of paper.

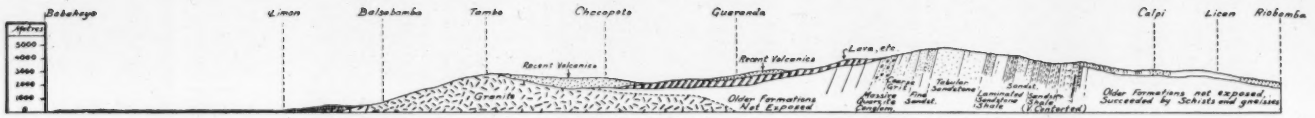

FIG. 1.—GENERAL SECTION FROM BABAHOYO TO RIOBAMBA, ECUADOR. Scale: 1·200,000.

outliers of limestone of the same type as the Guayaquil Limestone, the terrain occupying the ancient estuary of the Guayas River extends approximately for 50 miles almost at sea-level, as far as the western frontier of the Andes.

This latter range ascends abruptly from the lowlands as an elevated scarp, and rapidly attains a height of 14,000–16,000 feet. As will be seen from the section (Fig. 1) the geological formations found between Babahoya and Limon consist for the most part of river silts and muds of no great age, which are underlain by Tertiaries, and have been doubtless accumulated by the flooding of the river during the heavy rainy seasons. A considerable development of loose scree and coarse river detritus then follows, including gravel and boulders from the rivers draining the Andes, these deposits being associated also with recent volcanic material. It is of interest to note that the highest parts of the Western Cordillera are not infrequently covered by ejected volcanic detritus which has been derived obviously from such centres of eruption as Chimborazo and Tunguragua.

The most important igneous occurrence, however, is an extensive massif of light-coloured biotite-granite which, in this part of the country, forms the most westerly buttress of the Andes. In places, the surface of this granite mass has weathered into soft, kaolin-like deposit, below which are dark, ovoid segregations like "heathen". This granite outcrop extends for a considerable distance eastwards to an elevation of 8,850 feet, its easterly limit being obscured by newer deposits. Although it is impossible to give even an approximate age to this granite, the rock itself appears to be relatively fresh and, under the microscope, shows no sign whatsoever of secondary alteration (Plate XIX, Fig. 4).

From Chacopota to Guaranda no outcrops other than those in recent volcanic material are visible, though from the latter place to Riobamba an entirely different suite of formations, mostly sedimentary, are found. In Wolf's original map (2) a small occurrence of plutonic rock is indicated to the east of Babahoya, but this by no means gives a true idea of the extent of the intrusion.

Referring to the section (Fig. 1) it will be seen that an abrupt change in the geology takes place to the east of the granite mass described above. The actual contact between the latter and the succeeding formations to the east is unfortunately obscured by recent volcanic material, yet on the road from Guaranda towards Riobamba good sections of a bluish porphyritic rock are found, which indicate that this is a large dyke or similar intrusion.

The folia of the latter rock are inclined towards the west at a high angle. This hypabyssal form is different in every way from the more recent occurrence found at the town of Guaranda, which is a typical recent lava with non-mineralized vesicles elongated in the direction of flow.

The steeply inclined and faulted formations such as are indicated

in the section then follow, and they include massive quartzite conglomerates which are very compact and well cemented. These are succeeded to the east by a greyish sandstone series which range from coarse quartzite grits to fine-grained sandstones, the majority dipping towards the west at a high angle (75–85°). Dark grey shales, usually decomposed, are intercalated amongst the sandy members of the group, and it should be noted that the outcrops exposed at the mountain divide (over 14,000 feet) consist entirely of a hard, tabular sandstone.

The most easterly part of the section, i.e. towards the village of San Juan, includes an unusual buff-coloured limestone which contains foraminifera. Under the microscope this limestone is seen to consist of a mixture of small broken shells, isolated angular quartz grains, fragments of altered volcanic rock, and occasional foraminifera, the whole being cemented by a calcareous matrix (Plate XIX, Fig. 1).

Towards the east and north the stratified formations are covered by thick deposits of volcanic ejectamenta and lava flows, these having been derived from the nearby centres of eruption. At the

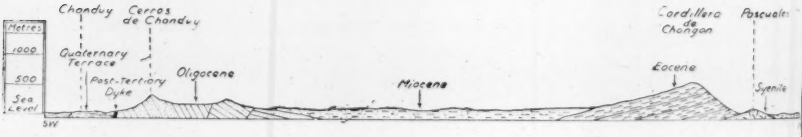

Fig. 2.—General Section from Pacific (Tertiary Coast-belt) to Pascuales.

town of Baños, and farther along the valley of the River Pastaza, schists and gneisses are found, all of which are steeply inclined and strike to the north (3, 4). Taking an approximate line of section, therefore, from the Pacific (Fig. 3) to the Western Cordillera we find:

(1) A broad and relatively low belt of Tertiary formations with which both plutonic and hypabyssal intrusions are associated.

(2) The biotite-granite massif which occurs towards the west of the Cordillera.

(3) The inclined and faulted sandstones, shales, and limestones forming the greater part of the western frontier range. These are succeeded to the east by a complicated group of schists, gneisses, and plutonic rocks.

According to Wasson and Sinclair in the paper above cited (3) the schists, gneisses, and granites seen along the north side of the River Pastaza, above Baños to Mera, form the ancient core of the Andes in Ecuador, and they are unquestionably older than the sedimentary series east of the mountains, viz. along the rivers of the Amazon basin.

The present writer is inclined to the opinion also that the granite and syenite intrusions, with associated flows of rhyolite, which occur near the sandstones and limestones of the Babahoya-Guaranda region, are younger than the rocks of the Eastern Cordillera which were investigated by Sinclair, and may indeed be Tertiary in age.

Wolf definitely indicates that the whole of the Western Andes are Cretaceous and, although certain foraminifera have been detected in the limestone collected from San Juan these forms may equally suggest Tertiary conditions, but until more definite palaeontological evidence is forthcoming from this region it is impossible to say whether the sedimentary formations of the Western Cordillera are Cretaceous or even earlier. Lithologically, there is a distinct similarity between the above deposits and those which have been determined as the Tertiary of the coast-belt, although it is impossible to make even an approximate correlation upon meagre evidence of this nature.

The Guayaquil Limestone rests upon an intrusion of syenite, the latter having uplifted and metamorphosed these sediments. This being the case it is, therefore, clear that the syenite mass must be post-Tertiary, and thus may be genetically related to the widely distributed hypabyssal dykes and sills which occur so commonly in connection with the Tertiary deposits of the littoral (5). How far this syenite is associated with the biotite granite of the Western Andes (Plate XIX, Fig. 2) it is impossible, as yet, to offer an opinion, but if it is of the same geological age, there is a strong likelihood that the sandstones, etc., of this range are also Tertiary and, in effect, that the major uplift of the Western Andes took place in Tertiary or post-Tertiary times.

Although there is ample evidence of the fact that the ancient formations constituting the core of the Andes in this region were folded prior to uplift, e.g. the schists and gneisses of the Eastern Cordillera, these being represented as denuded synclines, the geotectonic conditions of the west seem to suggest a broader and more recent uplift in relation to the structural disposition of the Tertiary rocks found in the coastal region.

The Guayaquil Limestone shows unequivocal signs of metamorphism, and not only is it intruded by basic dykes of a doleritic nature, but it rests upon the large boss of syenite referred to in the previous description. Brucite has been also recorded from the above deposit (2).

From the point of view of tectonics it is obvious that a major geofault of considerable displacement occurs along the western frontier of the Andes and extends for practically the whole length of the country from Peru to Colombia. It was along the depressed zone to the west that the Tertiary deposits were laid down, these probably extending for a great distance to the present coast. During the Tertiary and later Quaternary periods the littoral zone was in a state of crustal oscillation, the evidence for which is

indicated by the block-faulted and disturbed condition of the Tertiaries, and the respective terraces of the Quaternary, the latter indicating the several phases of uplift.

There is little doubt that the Gulf of Guayaquil had a much greater inland extension than is apparent at the present time: it originally followed the major fault scarp of the Andes. With the subsequent uplift of this zone the Gulf gradually diminished in size and left a wide expanse of low-lying land which is such a striking topographical feature between Guayaquil and the Andes proper.

It is considered by the writer that the igneous intrusions of the Ecuadorian coast have played a large part in the further development of the pre-existing geological structures found in the Tertiary formations.

Igneous rocks are also present in Peru but these, however, are of a different order and belong more to the Andes, and do not occur in any form of relationship with the Tertiaries. The Amotape Mountains consist of a spur from the main Andean range and are formed largely of slates, schists, quartzites, and other metamorphics. The same type of rocks form the Paita Hills and the Silla de Paita as well as the Cerros de Illescas farther south. They are everywhere closely associated with a granite intrusion from which pegmatites and quartz veins extend into the metamorphosed sediments. Close to the granite intrusion itself this metamorphism has been carried to an extreme, forming schists which have led several observers to consider them as pre-Cambrian (6).

One of the most important problems connected with the coast-belt of both Ecuador and Peru is the influence of regional tectonics upon the Tertiary formations, and although local variations are apparent in the structural geology of the same deposits in both countries, the fundamental causes are probably the same. Dr. Bosworth's work in Peru (11) led him to the view that the block-faulting visible in the Tertiary beds of the littoral, expresses the block-faulting of the underlying mountain rock, and further explains that the subsidence of the continental region west of the Andes, upon which the Tertiary deposits were accumulated, was the principal factor in the downward block-faulting which is now seen in these formations.

It is quite obvious, and it is recognized, that a considerable subsidence on a regional scale must have taken place in order to account for the sedimentation of approximately 25,000 feet of relatively shallow water deposits, yet we must consider, however, the exact geological time at which the subsequent block-faulting was accomplished. The faulting was obviously not induced during the initial subsidence movement of the continental shelf at the time when the Tertiary rocks were in the process of formation, and Bosworth suggests that the greater part of this structural adjustment happened during a late phase of littoral emergence, and hence the

Tertiary formations nearest the mountains (the outer spur known as the Amotapes) formed part of a large geofault which parallels the oceanic abyss to the west of the continent.

The block-faulting which is so characteristic a feature of the Tertiary sediments in both Ecuador and Peru is definitely of post-Tertiary and pre-Quaternary age, the deposits of the latter being practically horizontal, and they are structurally undisturbed.

Iddings and Olsson (6) express the opinion that the younger Tertiary strata of Peru have been faulted down against the older rocks, and that they dip away from the mountains at a low angle. Major faults having a throw as much as 5,000 feet are present in the Peruvian coastal zone, and the structures include uplifted faulted blocks as well as anticlinal folds.

There are profound differences in a structural sense between the Tertiary and the Quaternary formations. The faulted nature of the Tertiary strata in Peru (further complicated in Ecuador by the additional factor of igneous intrusion) is in striking contrast to the almost horizontal and unbroken terraces of the Quaternary beaches. The latter are now found at different levels above the sea and represent simple incidents in the general process of slow crustal elevation, with very little crustal warping. No faulting, nor tectonic manifestation of any sort, has been recorded in the Quaternary beds, and their disposition at the present time undoubtedly implies a regional uplift on a large scale, which probably extended for many hundreds of miles in this part of South America.

It is believed that the latter emergence was not confined solely to the coastal terrain, but it formed part of the epeirogenic earth-movement which has been in operation since the beginning of the Quaternary period, and included at least the Western Cordillera of the Ecuadorian Andes.

This crustal movement, however, which left no structural impress upon the stratified formations of the Quaternary, was of a distinctly different order from that which characterized post-Tertiary and pre-Quaternary time. At this period the Tertiary deposits were subjected to tectonic disturbance and the results are now evident in the form of uplifted faulted-blocks, anticlinal and other folds, local shatter-zones and, also, in Ecuador, the association of post-Tertiary massifs, dykes, and sills. The post-Tertiary movement signifies an uplift of the main Andean range with a relative tectonic drag of the Tertiaries which flank these mountains to the west. The uplift of the Western Andes, therefore, in its relation to the depressed coastal zone, has been the principal factor in the creation of the unusual structural features which are observed in the rocks of the region under discussion.

In north-west Peru the intricate system of faulted blocks is governed by several major faults, the latter having displacements of as much as 5,000 feet. The " master " faults appear to be directed more or less at right angles to the Andes in this region, and it is

quite possible that their presence in this narrow coastal zone is due to the proximity, and to the outward tectonic expression, of the Amotape Mountains, the most westerly part of the Andes in this section of the country.

Although similar master faults of this nature have not been observed in association with the Tertiary rocks of Ecuador, it must be remembered that the principal range of the Andes is situated at a much greater distance from the coast than are the Amotapes in Peru, and the transverse dislocations initiated by the Cordillera probably disappear towards the west without having affected the general structural disposition of the newer strata. On the other hand, however, major faults of considerable displacement undoubtedly occur in south-west Ecuador but they lie, in all probability, parallel to the main Andean uplift and are now obscured by the later Quaternary and Recent deposits which are found in the extensive basin of the River Guayas.

The Miocene deposits in Ecuador are less disturbed than the Oligocene and Eocene, and it is suggested that whilst the whole suite of Tertiary formations has been influenced by powerful tectonic forces, the maximum structural expression took place towards the end of Oligocene time, continued to a lesser extent throughout the Miocene, and finally died out before the deposition of the first Quaternary beds.

Although, as mentioned previously, a more or less continuous subsidence of the continental shelf must be assumed to have taken place in order to allow for the sedimentation of such a thickness of shallow water deposits, there is evidence of temporary " halts " during the general subsidence movement, these intervals being the cause of unusual geological phenomena. To quote one example, the Clay Pebble Bed of the Ancon region (Ecuador) has been described by different authorities as an extensive crush zone involving overthrusts, and conversely as an abnormal phase of true sedimentation caused by exceptional climatic conditions. If the latter, it signifies an erosion interval during Eocene times which, *per se*, must have developed during the major " halts " in the subsidence of the continental terrain.

According to Iddings and Olsson (6) the Pacific Fault off the coast of Peru has a general north-south trend and its position is marked by a fairly uniform slope of 6° to a depth of about 13,000 feet. Oceanic soundings taken by the British Admiralty and other bodies off the coast of Ecuador, also indicate a northerly extension of the same fault, and it is of interest to note that this is generally parallel to the geofault along the western frontier of the Andes which, in itself, is one of the most important tectonic features of the region.

Thus, between the Pacific Fault and the great geofault flanking the Western Cordillera of the Andes in Ecuador, we have a wide belt of Tertiary formations which have suffered dislocation and

"FOUNDER"-BRECCIA, AYAMPE POINT, ECUADOR.

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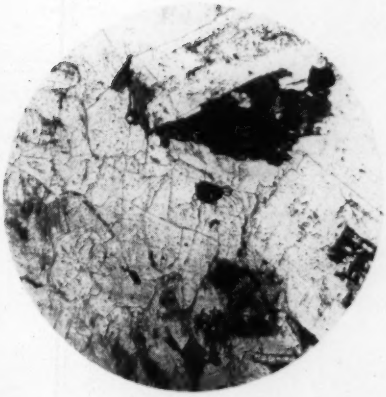

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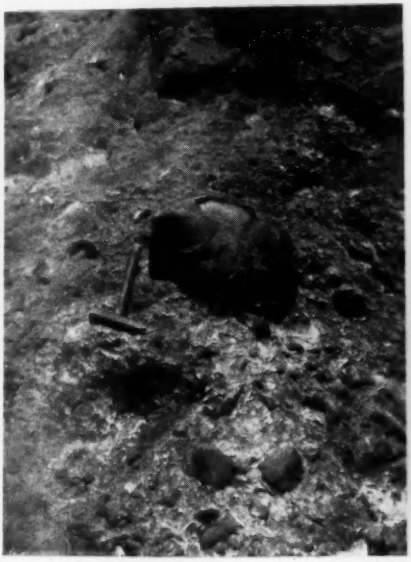

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Fig. 1.—Section of Limestone (× 25), San Juan, Ecuador.

Fig. 2.—Section of Biotite-Granite (× 25), Balsabamba, Ecuador.

Fig. 3.—"Contact"-breccia between Tertiary and Igneous, near La Libertad, Ecuador.

Fig. 4.—Hypabyssal Sill intruded in Tertiary Formations, Salango Point, Ecuador.

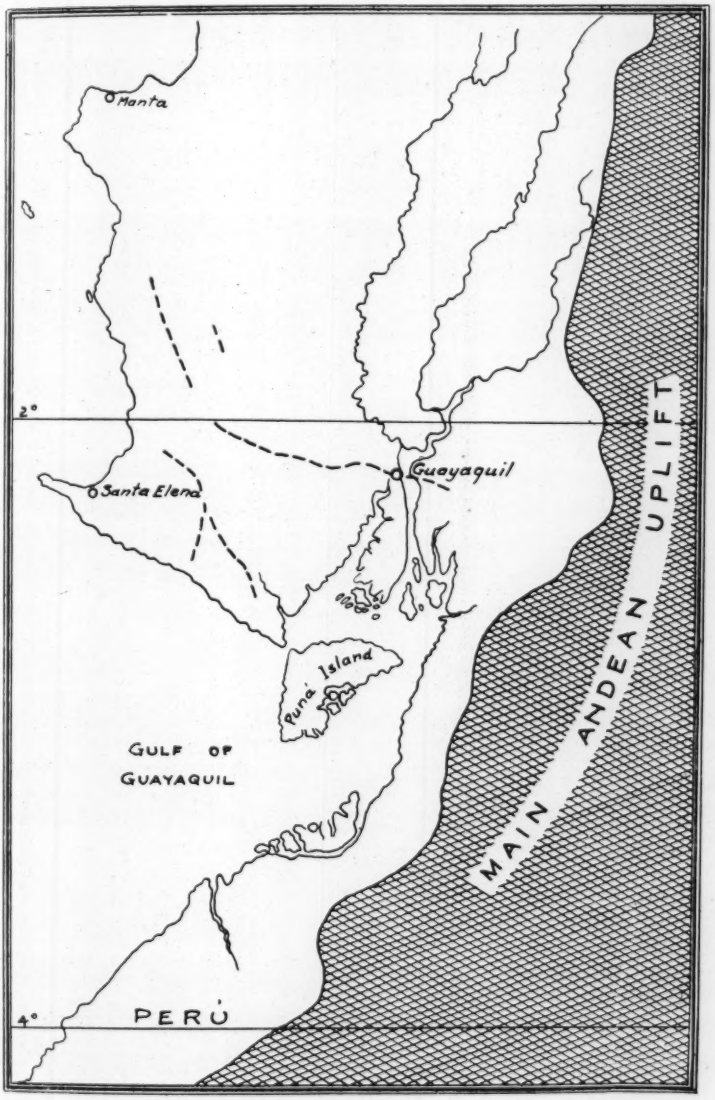

FIG. 3.—Sketch-map of Ecuador showing secondary flexures to the main Andean uplift. (Flexures indicated by dotted lines.)

compression as a result of the uplift of the Andes and the subsidence of the continental shelf. It will be generally conceded that certain structural phenomena occurring in association with the Tertiary sediments of this zone have been formed by the block-faulting of the older rocks in their tectonic relation to the Andean uplift: there is evidence also of tangential out-thrusting which took place during the period of this post-Tertiary movement.

Most of the local overthrusts, faulted blocks and similar dislocations of the Tertiary littoral may have been induced by a " downsliding of the continent into the ocean basin ", as suggested by Daly (7), but there is little doubt that the majority of these structural movements have been caused primarily by the uplift of the Andes combined with an out-thrusting of this range towards the Pacific. In north-west Peru, where the Amotape Mountains form the western range, the older rocks such as the Carboniferous and the Cretaceous, have been upthrust during this earth-movement. This may have been the fundamental idea of Kolberg's theory of " out-thrusting by thrust-wedges ", which was put forward in explanation of the structure of Ecuador (8).

It is difficult, at first consideration, to appreciate the magnitude of the tectonic forces which could be effective through a zone of sediments for a distance of over 100 miles, assuming, as one must, that the post-Tertiary behaviour of the Western Andes in Ecuador was the principal cause. This major earth-movement was expressed through the Tertiary strata by subsidiary stages, or zones of structural weakness, each of which materially assisted in the further dislocation of the sedimentary formations. In these cases, the shale elements of the stratification being less competent to withstand the tectonic compression than the sandstones, we find as an invariable rule that whilst the former are sheared, dislocated, and contorted to an extreme degree, the latter simply assume crescentic ridges, and form prominent escarpments in the general topography (Fig. 3).

The subsidiary episodes of tectonic adjustment in this special region can be divided, therefore, into two classes:—

(1) The major tangential flexures (usually expressed by the sandstones), and

(2) Post-Tertiary igneous intrusives which invaded and distorted the already disturbed and block-faulted strata.

The principal topographical unit to the west of the Andes in southern Ecuador is known as the Cordillera de Chongon, a range of Tertiary rocks which starts approximately near the city of Guayaquil and extends almost to the Pacific coast in a north-westerly direction. In addition to the Tertiary sediments there are igneous intrusions. Though not actually forming a direct spur of the Andes, as is the case of the Amotape Mountains farther to the south, the above range can be considered as a secondary flexure to the primary Andean out-thrust. Farther to the north the definition of this range is not so clear, and it appears as though the

structure is of a more distributed nature, such as faulted blocks and isolated escarpments.

With the exception of certain intermediate zones which have been laterally displaced during the earth-movement, most of the structure lines in the region have a direction roughly parallel to the north-west and appear to be subsidiary, in a tectonic sense, to the secondary flexures which have been already described. An extreme example of tectonic expression can be cited in the area covered by the map (Fig. 4), in which it will be noticed that the principal sandstone horizon, the Ancon White Sandstone, furnishes a useful index

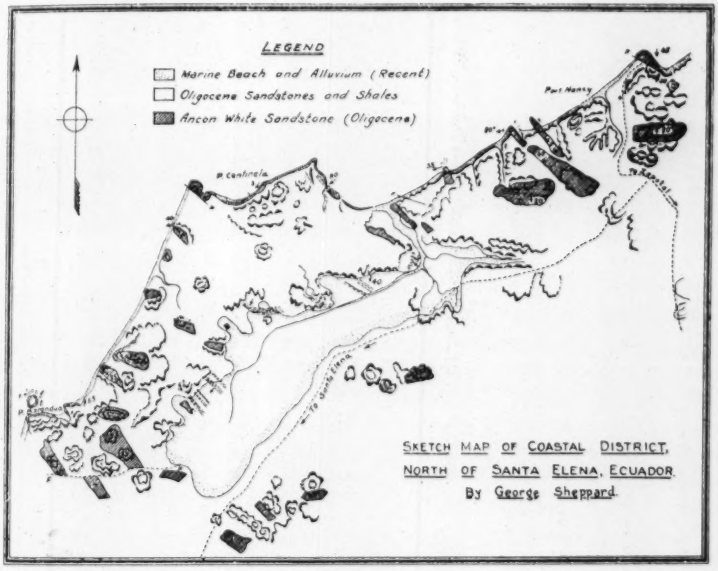

FIG. 4.

in the elucidation of the complex structure which is present. It will be observed that in addition to the north-westerly trend of the principal structure lines, a lateral movement has taken place, which accounts for certain conditions in the faulting. Local over-thrusts are not uncommon in this series and in the many cases where the shales occur intercalated amongst the sandstones, the shales are folded and contorted to an advanced degree, so much so that the original stratification has been entirely obliterated by the influence of the earth-movement, and in many instances a mylonitic shale complex is the result.

The post-Tertiary igneous intrusives which occur in south-west Ecuador have been already described (5).

It is necessary in the present discussion, however, to consider how far these igneous occurrences have affected the general structure

of the Tertiaries, whether they were intruded at a period subsequent to the maximum dislocation of the strata as outlined above, or whether, in some cases, they were the primary cause of certain structural phases.

Occurrences of extruded igneous rock have been recorded along the Pacific coast of Ecuador from Manta almost to the Island of Puna, a distance of over 120 miles, whilst the northerly extent of the same igneous series is unknown. These episodes are in the nature of sills and dykes which have invaded the Tertiaries (Eocene and Oligocene) and, as a result, must have influenced the nature of the existing structure.

It is the opinion of the writer that, with few exceptions, the recorded igneous intrusions followed the principal structure trends and thus were the consequence, and not the cause, of the tectonic folding. On the other hand, however, these later igneous rocks have undoubtedly advanced the disturbed condition of the same sedimentary formations.

It is recognized that the superficial extrusion of lava, either from true fissures or from volcanoes, is a common, though not general, accompaniment of mountain-building; and that this form of vulcanism is clearly an incident or after-effect of the orogenic movement, and not a primary cause. Deformation of the sedimentaries is not only induced by the actual intrusion of the igneous rock but a later volume decrease resulting from the cooling of the magma causes a subsidence or " foundering " of the overlying rocks, which leads to a further disturbance of the formations. According to Leith (9), " It is entirely possible that there were pre-existing structures which were followed by the intruding magma, but the earlier structures are more or less masked completely by the secondary structures produced by the intrusion itself."

In this region there is unequivocal evidence of the fact that igneous intrusions have been the primary cause of certain structural forms in the sedimentary deposits they have invaded, and it is indeed possible that major structures such as block-faulting and local overthrusting may have originated by a foundering of the strata upon the irregular cooling surface of a shrinking magma.

During the process of the intrusion of an igneous sill, for example, especially if the flow is directed in a more or less horizontal direction through relatively undisturbed strata, the latter will be deformed and possibly pushed forward in the direction of flow near the emergence zone of the igneous rock. Upon the subsequent cooling of this magma, a contraction in volume takes place during the crystallization, large quantities of gases are released which, no doubt, assist in the alteration of the invaded rock, and a gradual foundering of the sediments, accompanied by relaxational movements and stresses, takes place. The foundering of the sedimentaries upon the surface of a cooling igneous mass gives rise to block-faulting and local overthrusting, the latter being induced by the compressive forces

of the magma at the time of its intrusion. When the igneous rock has completely consolidated, the structures existing in the sedimentary rocks are further deformed as a result of the diminution in volume which follows the consolidation.

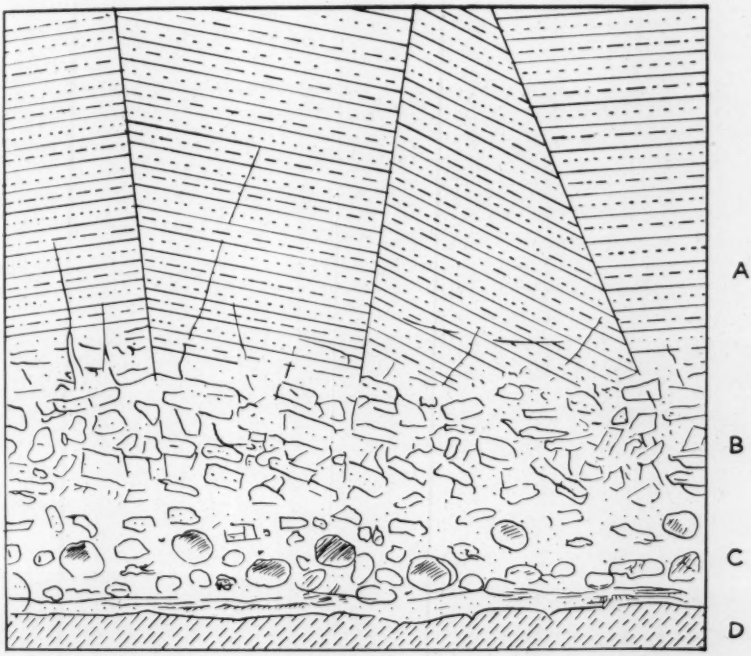

FIG. 5.—Diagram illustrating contact zone between igneous and sedimentaries. A, Block-faulted sandstones and shales. B, "Founder"-Breccia. C, "Contact"-Breccia. D, Surface of igneous.

An example which illustrates the above phenomenon can be seen at Salango Point, a small headland on the west coast of Ecuador, midway between Manta and Santa Elena. Marine erosion has here exposed a complete section which illustrates both the igneous sill and the structures it has induced in the superimposing Tertiary deposits. The surface of the igneous rock, in this case a grey dolerite, is hummocky, though practically horizontal, and it is devoid of faulting or jointing (Plate XIX, Fig. 4).

Immediately above occurs a few feet of contact or crush breccia, the individuals for the most part of igneous rock, which have the appearance of rounded boulders, and have doubtless been formed by the intrusion of the molten lava in its forward movement whilst

in contact with the sedimentaries. A zone of shattered sandstone then follows, heavily veined and occasionally silicified, which can be described as a true breccia consisting of angular blocks of sandstone or sandy shale, some of which have been included in the igneous flow, and displaced accordingly.

The general structure of this breccia, however, suggests that the shattering of the sedimentary rocks has been caused by their settling down upon the diminishing volume of the cooling sill. For this reason, a breccia of this type can be more correctly described as a "founder"-breccia, in contradistinction to the normal contact-breccia which occurs in association with the upper surface of an intrusive sill (Plate XVIII; Plate XIX, Fig. 3, and Fig. 5.)

Farther to the south, viz. at Ayampe Point, a founder-breccia is well displayed in section, and in this case the brecciated sedimentaries seen above the igneous have been completely cemented by silica into a homogeneous rock, this latter being an intermediate stage to a brecciated chert. Typical cherts are also seen in close association with the igneous, and add further to the knowledge which has been already published (10).

Block-faulted strata appear superimposing the igneous rocks at the localities cited, occurring normally above the contact and founder-breccias. This block-faulted structure may quite conceivably have been caused by the foundering of the sedimentaries in the manner described above and, in effect, it does not differ from the general block-faulted habit of the Tertiary formations found along this section of the Ecuadorian littoral (Plate XX).

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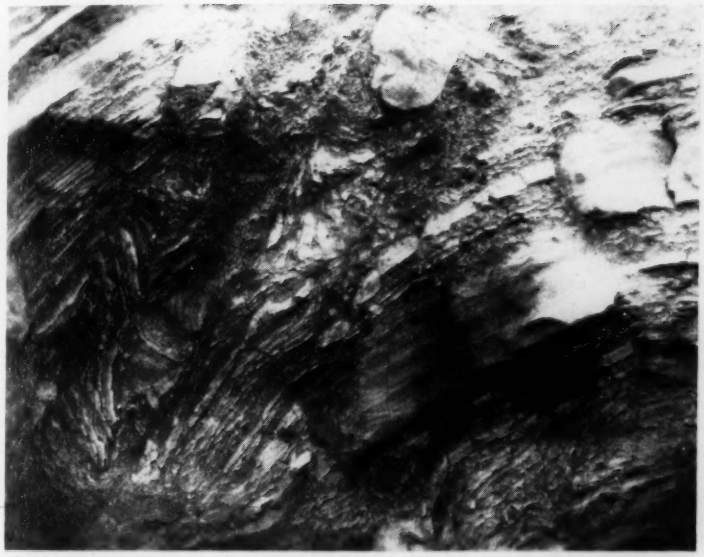

Dislocations in Tertiary Strata, near Ancon, Ecuador, probably caused by "foundering".

[*To face p.* 494

The Convection Current Hypothesis of Mountain Building.

By A. J. Bull, M.Sc., F.Inst.P., F.G.S.

In a previous paper in the Geological Magazine (1)[1] the hypothesis was suggested that mountains might result from the dragging together of sediments and other rocks by a convection current in the material below the crust. It may be useful to review the present position as to how far this idea has offered an adequate explanation of mountain and other earth structures.

What was envisaged in this first paper was that the surface of the earth might be deformed as a result of the unequal liberation of

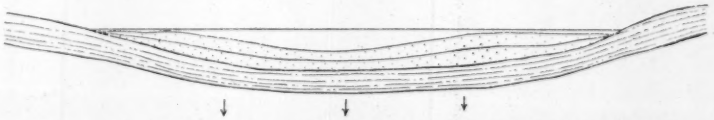

Fig. 1.—A sedimentation subsidence due to differential heating of the sub-crystal material.

radio-active heat in different parts of the sub-crustal material, and the consequent variation of density from place to place, perhaps partly produced by metamorphic changes, would result in a warping of the surface. There might thus be formed as the temperature differences increased a relatively sinking region in which sediments worn from the higher ground would accumulate (Fig. 1). The weight of the sediments themselves might aid in deepening the trough, and then, when the sub-crustal material had become hot

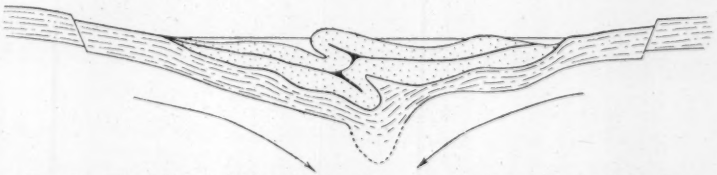

Fig. 2.—The folding of the sediments by a convection current, while the outlying regions are in tension.

enough for movement to take place, the part that is denser and presumably not so hot would begin to sink more rapidly. The material under the higher ground at the sides of the sedimentary subsidence would be dragged in, and the sediments then resting upon what would virtually be a contracting support would be folded, particularly in the centre (Fig. 2). Such folding might well start before sedimentation ceased. There would later result a

[1] Figures in parentheses refer to list of references at end of paper.

crumpled mass consisting largely of light sediments together with portions of the original layer of sial and intrusions of fluid material from below. This great thickening of relatively light rocks would sink into the viscous material below, but being light the folded mass would float, so that some of it would project above the normal surface as a folded mountain range (Fig. 3).

In a later paper (2) the writer discussed critically some of the outstanding hypotheses that have been advanced to explain the formation of folded mountains, and reasons were given for the failure of the thermal contraction hypothesis and others, and in the course of this criticism it was pointed out that the convection idea had as yet little evidence to support it. The suggestion was, however, made that it might provide a solution of the Gondwana problem by indicating a force that would drift the parts of the Gondwana continent to the positions they now occupy. Wegener and others have shown that strong stratigraphic and tectonic evidence exists for the breaking up of a great continent of Permo-Carboniferous times and the drifting of its various parts to positions

FIG. 3.—The light folded mass floating up to form mountains.

indicated by the distribution of the Glossopteris flora and the glacial deposits. In this paper it was suggested that a convection current rising under the central part of the great continent which is now Africa would drag the other parts away from this centre to the positions they now occupy in India, Australia, East Antarctica, South America, etc. As was further pointed out, this is in agreement with the statement that the rift valleys and faults of Africa indicate a tension outwards (3).

Further, the writer has indicated (4) that the Alpine nappes cannot have been formed by simple compression, but that material must have been removed from beneath the strata that are folded into the great recumbent folds. It was shown how nappes can be imitated on a small scale by applying forces in the same directions as would be applied by a " downward convection current ".

In a discussion on continental drift (5) Professor Holmes adopts the idea of convection currents as a cause of earth movements, particularly the large scale current previously suggested as rising under Gondwanaland and dragging its outlying parts away from its centre which is now Africa. Following Joly's ideas Holmes considers that the large continent may have acted as a great thermal blanket, and so caused the higher temperature which gave rise

to the upward convection current. He suggests that not only Gondwanaland but also Laurasia may have been acted on by a similar current and so dismembered. Holmes' statement that the convection current hypothesis is "consistent with the proved simultaneous occurrence of tension and compression" agrees with the earlier claim for the hypothesis.

In another paper (6) Holmes has elaborated the idea of convection currents to explain not only continental drift and mountain formation but many puzzling tectonic features. He postulates a planetary circulation in the sub-stratum somewhat similar to the planetary circulation in the atmosphere, and suggests that this may tend to drag land masses from the equator towards the poles, and points out how such currents acting in conjunction with convection currents arising under the sial masses of the continents may have moved what is now South Africa from the South Pole in Permo-Carboniferous time to its present position. He again discusses the breaking up of Gondwanaland and Laurasia, and argues that such drifting of continents is in agreement with the existence of the peripheral mountain systems with which the dismembered portions of these two ancient land masses are now surrounded.

Holmes considers that not only may the continents blanket the heat generated by radioactivity, and the consequent rise of temperature beneath them produce outflowing currents, but also the oceanic crusts may act similarly but to a less degree, and instead of assuming the direction of convection currents from these causes to be from a continent towards an ocean, he assumes both continent and ocean to generate their currents which meet at the coasts, and under the conditions of high temperature and pressure produced by the meeting of the currents, the magmas crystallize and form garnetiferous rocks such as eclogite, and the sinking of the eclogite due to its high specific gravity produces geosynclines.

While at this point the argument comes back to the original suggestion of a sedimentation subsidence being formed by the slow sinking of heavy rocks, some features of this scheme are certainly very speculative, particularly the formation of outward currents from oceanic areas instead of merely a flow from the high temperature region towards the region of lower temperature.

Among the elaborations of the hypothesis put forward by Holmes, the explanation of rift valleys is particularly ingenious. These he supposes to be due to a deep-seated compression over narrow belts of eclogite formed where two convection currents have met. The sinking of the heavy eclogite provides for the lowering of the floor of the rift valley, and the compression along the line for the curved thrust surfaces which have been observed.

The explanation of rift valleys is closely related to the original suggestion of convection currents in that it may be a phenomenon produced by the sinking of a band of heavy material. The median

areas of Kober, which Holmes also discusses, are probably cases where the sinking areas are wider, hence the folding effects on the surface rocks are most noticeable on the two edges, where they give rise to two mountain systems overturned away from each other.

In the work outlined above the two methods of attack upon the problem are different. The writer has taken the view that the cause of earth movements can best be ascertained by determining what forces could produce the existing structures, and it was a rough consideration of the matter along these lines that led to the hypothesis of differential heating producing firstly a sinking area and later a convection current which would fold the accumulated sediments, and also to the suggested dismemberment of Gondwanaland by a large convection current. Here the matter remained until Holmes adopted the idea, but his method of treatment is deductive. He assumes convection currents of various types, and then uses them to explain all the chief tectonic structures. This same deductive method of argument has unfortunately been used with nearly all the hypotheses that have been put forward from time to time to explain earth movements, and is one reason why so little real advance has been made. The fact that in discussing a number of hypotheses the writer included his own idea of convection in the critical survey (2), has apparently been taken by Holmes as an abandonment of the idea.

It would appear that this hypothesis does offer some explanation of mountain formation and earth movement (and the writer is inclined to the opinion that it will be found to be the real explanation), but it cannot yet be accepted as more than a suggestion. A theory of mountain formation must be capable of explaining all the phenomena of a mountain building episode, and must be in accord with all related facts. Among the questions upon which the author is working and experimenting are the formation of island festoons, the structures resulting from thermal contraction, and the relation of reversed folds and the applied force.

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(5) A. Holmes, *Mining Mag.*, xl, 1929, 205, 286, 340.
(6) A. Holmes, *Trans. Geol. Soc. Glasgow*, xviii, part iii, 1928–9, 559.

On an Orbicular Diorite from the Island of Alderney.

By S. R. Nockolds (Sedgwick Museum, Cambridge).

(PLATE XXI.)

Introduction.

WHILST studying the Bibette Head Granite, the writer had occasion to devote a certain amount of attention to the rocks with which it is in contact. In the region under consideration, these are essentially of dioritic type. The Orbicular Diorite was first found in a small embayment forming part of the west side of Corblet's Bay. It was found later in a less well developed fashion, at Saye Bay. It is quite possible that extended search would prove the presence of more. For the most part the orbicules are widely scattered, but a boulder was found at the Corblet's Bay locality which shows several associated with inclusions of a more basic rock. This boulder is now in the Sedgwick Museum, Cambridge.

The orbicules are surrounded by material which is coarser in grain than the normal diorite. It is a noteworthy point that, where the orbicules are developed, the diorite carries included fragments of a more basic rock.

The Inclusions of Basic Rock.

There would appear to be two types of these present. One type occurs as small elongate fragments with reaction zones between it and the surrounding diorite; the other type is seen on a smooth surface to be circular or almost circular in shape and has a homogeneous appearance.

(*a*) Elongate Inclusions: The example to be described was taken from the diorite in association with the orbicules, and is a dark, fine grained fragment. In thin section the inclusion is found to consist of a finely granular aggregate of felspar (now represented by sericite and very finely disseminated zoisite), actinolitic amphibole, some partially altered biotite and a chlorite allied to penninite which has probably replaced biotite. In addition, magnetite is abundant.

Towards the margin, magnetite increases rapidly and the amphibole and biotite crystals become larger. It would appear that the inclusion has been completely recrystallized. Between the inclusion and the diorite there is a well defined reaction zone which has a coarser grain than the inclusion itself. This is largely composed of grains of basic andesine and magnetite with lesser amounts of actinolite and biotite.

(*b*) Spheroidal Inclusions: Associated with the orbicules there are spheroidal inclusions which resemble the orbicules in shape and size, but are homogeneous in appearance. These are the ones which are circular when seen in cross-section on a smooth surface. They are dark in colour and medium in grain.

In thin section, remnants of original augite are seen surrounded by a rim of pale green actinolite. In other parts the actinolite has completely replaced the augite. Sometimes the actinolite encloses pseudomorphs of another mineral and these pseudomorphs are also present in places without the enclosing amphibole. They are obvious replacements of olivine and, in many instances, the original alteration cracks of the olivine can still be seen. The mineral which has pseudomorphed the olivine is yellowish or yellowish-green in colour and moderately pleochroic. It has straight extinction, is biaxial negative, and has a birefringence of about ·012. These optical properties agree with those of antigorite. Sometimes it appears as if the actinolite was replacing the antigorite. A little bleached biotite is present. The felspar is all altered to a mass of white mica with subordinate granular zoisite and calcite. In most cases this alteration is accompanied by a development of an almost isotropic chlorite associated with a certain amount of antigorite. Whereas in the elongate inclusion the white mica was in minute flakes, in these inclusions the flakes are quite large. A certain amount of magnetite and a little secondary albite complete the section. From the above description it will be seen that the original rock must have been an olivine-gabbro, and its present mineral assemblage is due to alteration of a hydrothermal nature.

The Orbicules.

On a smooth surface of the rock, the orbicules appear approximately circular in shape with a well marked concentric structure consisting of alternate lighter and darker rings. More rarely, a slight radial structure is also found. The orbicules as a whole have a quite definite greenish colour. The number of concentric zones varies in different examples. Occasionally the orbicules have been flattened. The following are some typical measurements across the maximum and minimum diameters as seen on a flat surface: 23 mm. × 16 mm., 32 mm. × 28 mm., 44 mm. × 38 mm., 48 mm. × 40 mm. One was noticed at the time of visiting which was a good deal larger. The average range in size of the orbicules is also the average range in size of the spheroidal inclusions. In order to gain some idea of the structure, a thin section has been cut through a complete orbicule and the diorite with which it is in contact. The specimen chosen showed five distinct zones and a nucleus.

1. The Nucleus: The nucleus is composed of predominant felspar with only minor quantities of amphibole, biotite, and chlorite. The felspar is now completely pseudomorphed by white mica in quite large flakes associated with a little disseminated zoisite. The original cleavage directions of the felspar are, however, still well displayed. This is due to the fact that mica was deposited

along the cleavage planes and the section has been cut almost at right angles to them. The amphibole, which only occurs here in minor quantity, is a greenish blue, slightly fibrous variety. It is strongly pleochroic with X pale yellow, Y apple-green, Z greenish blue. It has positive elongation, is biaxial negative with $2E$ fairly large, and has $Z \wedge c = 20$ degrees. There is little doubt that this is an aluminous amphibole containing a certain percentage of the hastingsite molecule. It contains inclusions of magnetite but these are not abundant. Occasionally, inside this greenish blue amphibole, remnants of antigorite may be found. Associated with this amphibole there is a certain amount of bleached biotite. Almost all stages of bleaching can be found from that in which the pleochroism is slightly paler brown than usual, to that in which the biotite is almost colourless and only feebly pleochroic in shades of green. In the latter instance it may resemble chlorite rather strongly but can be distinguished by the fact that it retains the birefringence proper to biotite. There is, however, a little pale green, almost isotropic chlorite associated with the biotite and the amphibole.

2. The First Zone: This zone is a narrow one composed mainly of the greenish-blue amphibole, bleached biotite and a little chlorite with subordinate felspar which is completely altered in a manner similar to that of the nucleus. This is the case with all the felspar which occurs inside the orbicule.

3. The Second Zone: This is a felspar-rich zone and is of greater width than zone one. In this the amphibole, biotite, and chlorite are present in minor quantities, but in greater amount than in the nucleus.

4. The Third Zone: This is, again, a narrow one and is similar in composition to zone one.

5. The Fourth Zone: Is a felspar-rich zone similar to, but rather wider than, zone two. The ferromagnesian minerals are present in minor amounts and are rather less abundant than in zone two.

6. The Fifth or Outer Zone: This is, once more, a zone rich in ferromagnesian minerals. It is wider than the other two and differs from them in containing the diorite amphibole, to be described below, in addition to the usual greenish-blue amphibole and bleached biotite.

The Surrounding Diorite.

The diorite which immediately surrounds the orbicules is composed essentially of plagioclase felspar and hornblende with minor amounts of biotite and quartz. The texture is normally dioritic and of medium to coarse grain.

The felspar is well twinned on the albite law and the maximum extinction angle obtained on symmetrical albite lamellæ was 17°,

indicating a basic oligoclase or acid andesine. Most of the felspar is rather badly altered with the separation of minute flakes of white mica together with a considerable amount of dusty zoisite and calcite. Thus the alteration of the felspars in the orbicule and in the surrounding diorite, whilst of the same nature, has been quite different in intensity. In the one case we have large flakes of white mica developing, in the other case minute flakes.

The amphibole of the diorite is also of quite different nature to that found in the orbicule. It is a green variety with X pale yellowish, Y pale brownish green, Z medium green. It has positive elongation, is biaxial negative with $2E$ medium and with $Z \wedge c$ 16°. Twinning on 100 is very common.

The biotite, which is usually associated with the hornblende, is again different to that found inside the orbicule. This biotite is a quite normal brown variety, generally partially altered. The alteration, however, does not consist in bleaching but in a direct transformation to penninite. There is a little interstitial quartz quite free from all signs of strain; the accessories are ilmenite, magnetite, and apatite, the last two being of common occurrence and usually enclosed either partially or wholly by the hornblende.

The Normal Diorite.

This is very different from the material which surrounds the orbicules and inclusions. It is of medium grain but less coarse than that surrounding the orbicules and is composed, for the most part, of plagioclase, felspar, and pyroxene. The felspar is a very basic andesine but little altered, and the pyroxene an almost colourless augite often having a well developed striation parallel to 001. Simple twinning on 100 is not uncommon. In part, this augite is replaced by the green amphibole characteristic of the diorite immediately surrounding the orbicules. This green hornblende also occurs by itself. In addition to these constituents, there are chloritic pseudomorphs of a mineral which may originally have been hypersthene, subordinate brown biotite usually associated with magnetite, and a certain amount of interstitial quartz. Finally a little apatite is present. The junction between this diorite and the diorite which encloses the orbicules and inclusions is marked by a narrow band which is slightly darker than either of the two types.

This normal diorite has a much fresher appearance than the other variety. The difference between them can be accounted for by supposing that the diorite immediately surrounding the orbicules and inclusions was richer in volatile constituents than the normal diorite. This would also account for its coarser grain. Bowen has shown that theoretically the presence of inclusions in a magma should emphasise the later products of the reaction series. In the present instance, the normal rock is a basic diorite but the rock

surrounding the orbicules and inclusions is a more acid variety. This is analogous to the rims of pegmatite formed round inclusions, rich in ferromagnesian minerals, which have been found in certain granites. In both cases it seems likely that the volatiles have played an important, if not dominant, part.

Some Theoretical Considerations.

The most detailed study of orbicular rocks which has yet been made is that contained in a recent paper by Sederholm,[1] where also, there are references to most of the previous literature on the subject. In the course of this paper Sederholm comes to some very interesting conclusions. Some of these will now be briefly mentioned. His first is that orbicular structure is of exotropic rather than eisotropic nature. He does, however, allow one exception to the general rule, saying : " In the spheroids which possess a central nucleus of foreign rock, the composition of which is very different from that of the orbicular rock itself, there may be formed, through its progressive assimilation by the magma still circulating in the spheroid, next to the fragment a magma zone which has according to the observations of Frosterus and Cole, even been able to penetrate, in an eruptive way, the surrounding outer shell, forming veins in it which join with the still fluid magma that surrounds the spheroids. It is evident that this inner zone of magma may then be able also to react upon the adjacent parts of the enveloping shell which have therefore partly been replaced by a granite-like rock. The ' stratified ' shells have, in this case, not been deposited on the next inward lying shells in their present composition, but on earlier existing shells which have later been changed by a kind of autopalingenesis." Even here it will be noted that he postulates an original exotropic structure.

Secondly, he concludes that all spheroids have been formed around a nucleus, but that this nucleus need not necessarily be a rock fragment or the alteration product of it. Thirdly, he concludes that spheroids are formed from the crystallization of a molten magma and, finally, he emphasizes the fact that viscosity must have been high, thus hindering free diffusion and concludes that the concentric zoning of the spheroids is due to fractional crystallization during which the material of each individual shell was always derived from the nearest surrounding zone of magma.

What support does the present example offer to these various conclusions ? In the first place there seems to be some connection between the spheroidal inclusions and the orbicules. They both differ from the surrounding diorite in the alteration of their felspars and in the more obviously hydrothermal nature of their minerals. It is quite obvious that they were formed in a more " watery " or volatile environment than the surrounding diorite which, in its

[1] J. J. Sederholm, *Bull. Comm. Geol. Finlande*, No. 83, 1928.

turn, must have contained more volatile matter than the normal diorite magma. That is to say, instead of forming in a highly viscous medium, the orbicules have been formed in a medium which must have been a good deal more fluid than that of the normal diorite magma. How then, did these orbicules crystallize from such a medium and yet retain the slow diffusion necessary for the formation of a concentric structure ? The answer is surely to be found in the fact that they never crystallized at all as such from a liquid magma but are the products of reaction between the magma and solid inclusions. It will be remembered that remnants of antigorite were found in the greenish blue amphibole of the orbicule. This suggests their derivation from material similar to that of the spheroidal inclusions. These inclusions have the same shape as the orbicules and their size is comparable to that of the orbicules so that it seems reasonable to suppose that spheroidal inclusions similar to those found may have been transformed into the orbicules. It only remains to be seen whether this transformation could take place.

The outer zone of the orbicule is mainly composed of ferromagnesian material. The inclusion can provide the magnesia and some of the iron necessary for the formation of this zone, but in order that amphibole and biotite may be precipitated, the magma must provide alkalies, alumina, and probably some iron as well. Further there will be an optimum concentration of these various constituents which will favour the formation of the minerals. When reaction first starts there is plenty of material from the magma available and so a shell of ferromagnesian minerals is built up. As reaction proceeds and the shell becomes thicker, diffusion is hindered and eventually the concentration of the substances provided by the magma falls below the minimum necessary for the formation of the amphibole and biotite. Consequently no more can form for the time being. The concentration of the material provided by the inclusion will also have fallen to a greater or lesser extent. Thus, until the concentration of the materials has again reached the optimum value there will be no further precipitation of any great amount of these minerals. Therefore, during this period, the zone which is forming will be felspathic in nature. When the concentrations have reached their optimum again, another zone of ferromagnesian minerals will be formed and will continue to form until one of the concentrations drops below its minimum value. Then another felspathic zone will start to form. Either the material provided by the inclusion or the material provided by the magma may fall below the necessary minimum, and, in either case, precipitation must cease. The failure of one set of constituents to reach the optimum concentration at the same time as the other set may lead to the piling up of the latter before precipitation sets in again. So the process will go on building up successive zones alternately rich and poor in ferromagnesian

minerals until the inclusion is used up or until crystallization of the magma prevents any further reaction. In this way, a fragment of the inclusion may be left at the centre or, as in the present instance, there may be little or nothing left at the centre to betray its former presence. In this way, again, there would be no crystallization direct from a liquid magma, but the nucleus would be the last portion to form and would thus account for the injection phenomena noted by Frosterus[1] and Cole.[2] The ending of the formation of a spheroid would not be due to the fact that the magma had become too liquid to allow slow diffusion, as Sederholm suggests, but to the fact that all the inclusion had been used up or to the fact that crystallization of the magma had prevented further reaction. The number of zones formed will, of course, depend partly on the initial size of the inclusion, partly on the length of time allowed for reaction and also on the osmotic pressure of the various constituents necessary for the formation of a given zone which in turn, will depend on their concentrations in the magma or in the inclusions and on the temperature. No doubt there are many other factors which must also play a part. The mineral assemblage of the orbicules and the alteration of their felspars suggests a rather low temperature, in the present instance, and further suggests that the volatiles may be important as carriers of material during the reaction period.

The radiate structure of the orbicules is not well shown in the present examples as it is in many others. Where it does occur, it may mean rapid crystallization due to viscosity, but it may also mean, as Schade's work has shown, that the substance in question has a strong tendency to crystallize. It is quite certain also, that the formation of concentric zones necessitates an absolutely quiet magma, as has been proved experimentally by the recent work of Schubert.[3] If there is movement in the magma, then the outer rim of material is carried away and strewn about as soon as it has formed, leaving the magma in contact with the inclusion all the time and thus merely leading to its partial or complete dissolution without the formation of any zonal structure.

Summing up, we may say that the orbicules in the present example appear to have been formed by reaction between the dioritic magma and spheroidal inclusions. They have not been formed by direct crystallization from a liquid magma and they are eisotropic rather than exotropic. Further, the orbicules show but few traces of the inclusions from which they were formed. Consequently, even if an orbicule has no remnant of an inclusion at its centre, it does not necessarily mean that it has not been formed from an inclusion which was completely dissolved. Finally,

[1] B. Frosterus, *Bull. Comm. Geol. Finlande*, No. 4, 1896.
[2] G. A. J. Cole, *Sci. Proc. Roy. Dublin Soc.*, vol. 15, 1916, 141.
[3] E. Schubert, *Kolloid Zeitschrift*, 35, 1924, 219–20.

the magma in which the orbicules have been formed does not seem to have been at all viscous, in fact all the evidence points in the reverse direction. It will thus be seen that the present example appears to lead to conclusions almost entirely opposite to some of those arrived at by Sederholm. It is not suggested, however, that all orbicules have arisen in the manner outlined above. Doubtless there is more than one way in which these interesting structures can form.

EXPLANATION OF PLATE XXI.

FIG.

1.—Thin section of the Orbicule described about 1¼ times natural size. Notice the difference between the amphibole of the orbicule and that of the surrounding diorite, and also the more decomposed appearance of the felspar inside the orbicule.

2.—Photograph of rock surface showing the homogeneous spheroidal inclusions which are associated with the orbicules.

Scottish Pyroxene-Granulite Hornfelses and Odenwald Beerbachites.

Contact-metamorphosed Scottish igneous rocks of Tertiary age and their bearing on the origin of the so-called beerbachites, gabbro-porphyrites, and gabbro-pegmatites of the Odenwald.

By A. G. MACGREGOR, M.C., B.Sc.

(PLATES XXII AND XXIII.)

CONTENTS.

I. INTRODUCTION.
II. THE CONTACT-METAMORPHOSED SCOTTISH TERTIARY IGNEOUS ROCKS.
III. THE BEERBACHITES (GABBRO-APLITES), GABBRO-PORPHYRITES, AND ASSOCIATED ROCKS OF THE ODENWALD.
IV. DISCUSSION AND CRITICISM OF THE ODENWALD EVIDENCE.
V. ROSENBUSCH'S RECORDS OF SUPPOSED OCCURRENCES OF BEERBACHITE DYKES IN SCOTLAND.
VI. CONCLUSIONS.
VII. ACKNOWLEDGMENTS.
VIII. REFERENCES.

I. INTRODUCTION.

FOUR years ago Klemm (1926,[1] pp. 111–15) showed that the so-called beerbachites and gabbro-porphyrites of the Odenwald are not, as was previously supposed, dykes cutting the Frankenstein gabbro, but hornfelsed (granulitized) inclusions in the gabbro. Within the last few months has appeared the Geological Survey Memoir on the last of the great Tertiary igneous complexes that awaited detailed study in Western Scotland (Richey and Thomas, 1930*a*). In this publication the authors have given much new

[1] Dates in parentheses refer to References at end of article.

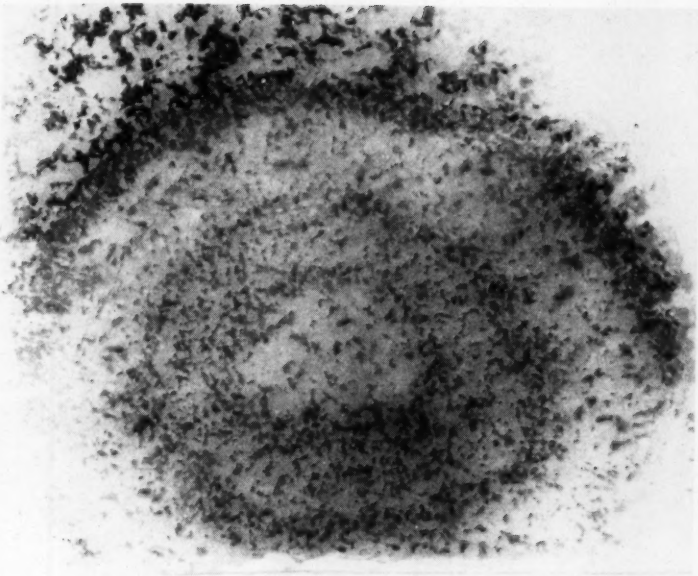

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Fig. 1.—Thin Section of Orbicule. × 1·25.

Fig. 2.—Boulder with Orbicules, Alderney.

[To face p. 506

information on the nature and mode of occurrence of pyroxene-granulite hornfelses associated with gabbros. Similar rocks are well known from the earlier work of Harker, Thomas, Bailey and others, on the Tertiary gabbros of Skye and Mull (Harker, 1904; Thomas and Bailey, 1924).

Klemm regards the granulitized inclusions in the Odenwald gabbro as hornfelsed *sediments*. The very similar Tertiary granulites of Western Scotland have been shown to be highly metamorphosed basic *igneous rocks*. The object of this paper is to make a critical comparison of the nature and mode of occurrence of the granulitic hornfelses of the two countries. The facts regarding the Scottish rocks will first be summarized, and detailed consideration will then be given to Klemm's evidence for the postulated sedimentary origin of the Odenwald beerbachites.

II. The Contact-Metamorphosed Scottish Tertiary Igneous Rocks.

In the Scottish islands of Skye, Mull, and Rum, and in the peninsula of Ardnamurchan, the contact-metamorphism of Tertiary basaltic lavas, around plutonic intrusions, was early recognized (Geikie, 1869, p. 73; 1871, p. 282; and 1888, pp. 104, 127–9, 136–42, 155, 159, 165–8, 183; Judd, 1890; Geikie, 1896, pp. 333, 385–7; and 1897, vol. ii, pp. 276, 337–40, 355–7, 362, 399, 404).

Brief petrographic accounts by F. H. Hatch and by A. Harker were included by Sir A. Geikie in his publications of 1888 and 1897. Detailed descriptions have since been written by Harker (1904, pp. 51–3, 115–16) and by Thomas (1924, pp. 152–5, 160, 253; and 1930*a*, pp. 232, 237, 240, 241, 288, 313, 317).

The lavas (olivine-basalts of various types) have as a rule been considerably weathered, or decomposed by other agencies, before they were subjected to high-grade contact-metamorphism. In the less highly metamorphosed rocks the original felspar-plexus may still be recognized, but the individual laths are often found to have developed "scalloped" (Schwartz, 1924*a*, p. 116) edges owing to marginal and interstitial recrystallization (Pl. XXII, Figs. 4 and 6). The ferromagnesian minerals recorded in the groundmass of such partially granulitized rocks are hornblende, biotite, augite, and iron-ores.

Only under conditions of relatively very high temperature does the felspar-plexus of the original rock become unrecognizable owing to complete recrystallization (granulitization). This very high-grade metamorphism is particularly associated with the more basic plutonic intrusions (especially gabbros and eucrites). In the writer's opinion this is largely because the temperatures of basic magmas are higher than those of acid magmas (cf. Schwartz, 1924*a*, pp. 131–3; Bowen, 1928, pp. 173, 185; Larsen, 1929, p. 94).

Where complete, or practically complete,[1] recrystallization has been effected, the granulitic mosaic is described, in Skye (Harker, 1904, pp. 52, 115), as consisting of augite, labradorite, and little crystals of magnetite, in some cases with olivine in addition. With the possible exception of olivine (see below, however) all are said to be newly-formed minerals. In Mull the component minerals are biotite, augite, hypersthene, labradorite, and magnetite, sometimes accompanied locally by brown hornblende or olivine. Such granulites are very similar to those described by Harker from Skye (Thomas, 1924, pp. 152–5).

The writer has examined many of the Geological Survey slices of contact-metamorphosed lavas from Skye and Mull. There seems no doubt at all that in some at least of the Skye lavas olivine (fayalite) occurs, as it does in Mull, as a mineral newly formed by contact-metamorphism in the recrystallized groundmass, and round the edges of amygdales.

Such pyroxene-granulites as those described above are in many instances proved by very clear evidence to be the metamorphosed representatives of basaltic lavas. Thus in some cases field relations show that they correspond to less highly altered lavas of outer aureole zones; in other instances the plagioclase phenocrysts that characterize many of the lavas have either remained stable under conditions that brought about groundmass granulitization (Pl. XXII, Figs. 4 and 6), or, if partly chloritized before metamorphism, may be represented by patches of clear recrystallized labradorite enclosing biotite, and strung through with granules of pyroxene (Thomas, 1924, pp. 154, 155). Again, as we have seen, original amygdales are sometimes still recognizable (Harker, 1904, pp. 53, 115; Thomas, 1924, p. 154). Harker pointed out in Skye that, under the high-grade metamorphic conditions that produced granulitization, augite and felspar are the minerals of the metamorphosed amygdales.

In Ardnamurchan there are numerous instances of basalt lavas granulitized by gabbro and eucrite. As in Skye and Mull, original porphyritic and amygdaloidal structures are often still recognizable. The minerals of these granulites are monoclinic and rhombic pyroxenes, plagioclase, iron-ore, and biotite (Thomas, 1930*a*, pp. 237, 241, 317).

Harker pointed out the close resemblance of the granulitized basalt lavas of Skye to the "pyroxene-granulites" of Continental petrographers. In doing so he called attention to the resemblance between the highly altered amygdales of Skye and some of the curious eye-like structures found in the pyroxene-granulites of Saxony (Harker, 1904, p. 53).

Some of the pyroxene-granulites of Skye are found as masses enclosed in the gabbro-complex (Harker, 1904, pp. 115–16). Their close resemblance to the granulites produced by the metamorphism

[1] Granulitization may be complete in one part of a rock-slice, and incomplete in another.

of basalt lavas in the innermost zones of the plutonic aureoles, and the presence in them of oval spots like much-changed amygdales, led Harker to regard these masses as highly reconstructed enclosures of basalt lava. He states that it is possible that two distinct rocks have been confused together, viz. a granulitic variety of the gabbro, and metamorphosed lava closely resembling it. He mapped, however, as metamorphosed basalts only those rocks that afforded some positive evidence of such an origin. He goes on to say: "Rosenbusch's suggestion[1] that Judd's granulitic gabbros[2] correspond to the 'beerbachite' of Chelius (an aplitic rock occurring as small dykes and veins in gabbro) seems to be based on a misunderstanding. We have not observed any rock comparable with beerbachite in Skye, the veins that traverse the gabbro being of quite other types." This statement of Harker's will be referred to again later on (p. 518), but first certain pyroxene-granulite hornfelses of Mull and Ardnamurchan will be considered.

In the Ben Buie gabbro-complex of Mull granulitic rocks, some showing mineral-banding, occur in the neighbourhood of Loch Fuaran. Thomas (1924, pp. 252, 253) has described them as consisting of hypersthene, augite, labradorite, and magnetite, sometimes with olivine in addition. The pyroxene may combine on occasion an ophitic with a granulitic structure. In many instances the mineral composition varies in different bands, and some specimens show an equigranular mosaic structure. Thomas considers the true nature of such rocks to be a matter of some uncertainty, but says that it is clear from a variety of evidence that they have resulted from the recrystallization of earlier basic igneous rocks, such as banded gabbros, early basic intrusions and basalt lavas. He says that this interpretation is to be accepted *although in some cases the rocks reproduce the characters of that type of micro-gabbro known as beerbachite*, and draws a comparison with Harker's "granulitic gabbros" or pyroxene-granulites of Skye. In some instances similar granulitic rocks in this district of Mull can be definitely proved from their field relations to have resulted from the metamorphism, by the gabbro, of an early dolerite sheet.

In some of the gabbro and eucrite masses of Ardnamurchan there are enclosures of granulitized igneous rocks that occur as xenolithic sheets or bands (Plate XXIII), or sometimes as angular fragments. They are similar to the granulitic masses in the gabbros of Skye and in the marginal portion of the Ben Buie gabbro-complex of Mull. The enclosures are regarded as remnants of rock-masses that were solid before the intrusion of the gabbro or eucrite in which they are now enveloped. They do not all have a similar origin—many were originally gabbroic rocks; others were early cone sheets or possibly basalt lavas.

[1] Rosenbusch, 1896*a*, p. 492.
[2] See p. 517 below.

The Ardnamurchan evidence shows that very frequently the major intrusions had early-consolidated margins against the country rock, and that these became granulitized and enveloped in the later uprising magma. The granulitization was probably effected before the included masses reached their present position, and possibly before they were stripped from the solid wall of which they originally formed a part (Thomas and Richey, 1930*a*, pp. 221, 222, 229–31).

Xenolithic granulites consisting of olivine, basic plagioclase, and magnetite, or of olivine, augite, spinel, and basic plagioclase, are regarded as recrystallized allivalitic gabbros or basic eucrites of early consolidation (Thomas, 1930*a*, pp. 232, 308, 317). Some granulites composed of olivine, augite, hypersthene, basic plagioclase, and magnetite may be supposed to represent either enclosures of granulitized fine-textured gabbro, or of recrystallized basalt lava. Other granulitic enclosures represent dolerite sheets.

The hypersthene-gabbro of Ardnamurchan Point, in addition to granulitic igneous rocks, locally encloses near its margin sapphire-bearing xenoliths consisting essentially of green spinel, basic plagioclase, and blue to colourless corundum. The sapphire-rock is associated with a hypersthene-olivine granulite that is regarded as representing the early-consolidated outer margin of the gabbro. This marginal gabbro, with inclusions of aluminous country rock (see below), was granulitized and disrupted by the later intrusion of the main mass of the gabbro. There is evidence that is said to show that the composition of the sapphire-bearing xenoliths has not been sensibly altered by exchange of material with the surrounding granulite. They are therefore thought to be rocks whose highly aluminous and ferruginous nature is original. The sapphire-xenoliths are thought to represent, most probably, " bole " produced by the contemporaneous weathering of the local Tertiary basalt lavas invaded by the gabbro (Thomas, 1930*a*, pp. 222, 233–5). These corundum hornfelses will be referred to again (p. 512) in connection with somewhat similar rocks found in the gabbro of the Odenwald.

It will now be clear that for many years British geologists have recognized the close resemblance that exists between the beerbachites of Chelius and the granulitized basic igneous rocks of Skye and Mull. Chelius, however, had mapped and described the rocks to which he gave the names beerbachite, gabbro-porphyrite, and gabbro-pegmatite, as occurring in the form of dykes that cut, and were therefore younger than, the Frankenstein gabbro mass of the Odenwald (Chelius, 1892, pp. 1–13). Until recently there was no definite reason to doubt the observations of Chelius, and therefore Harker and Thomas naturally considered that no true analogy seemed to exist between the beerbachites of the Odenwald and the pyroxene-granulite hornfelses of Scotland.

In 1928, however, Dr. Conrad Burri, of Zürich, drew the attention of some of his Scottish friends to a recent paper on beerbachites by

Professor Klemm of Darmstadt (Klemm, 1926, pp. 111–15). Through Dr. Burri the writer got in touch with Professor Klemm, who very kindly sent a copy of the publication in question, along with other relevant literature and some rock specimens. One section of Professor Klemm's 1926 paper is entitled " On the so-called ' Gabbro-aplite (Beerbachite) ' of the Odenwald ". A summary of Professor Klemm's results will now be given.

III. The Beerbachites (Gabbro-Aplites), Gabbro-Porphyrites, and Associated Rocks of the Odenwald.

Without going into detail it may be stated that Professor Klemm has shown beyond all doubt that the beerbachites, gabbro-porphyrites, and gabbro-pegmatites of Chelius do not occur as dykes later than the gabbro, but as masses of older rock caught up, metamorphosed, and granulitized by the gabbro. Professor Klemm describes the so-called beerbachites as possessing typical hornfels structure (" Bienenwaben- or Pflaster-structur "). Diallage, for the most part with irregular boundaries, lies in an aggregate of more or less rounded or hexagonal plagioclase grains. Sometimes larger hornblendes are also present and enclose felspars poikilitically. Many varieties are essentially hornblende-felspar rocks, true unsheared amphibolites; in others the place of hornblende is wholly or partly taken by hypersthene or biotite. Abundant iron-ore is also present. Professor Klemm does not mention the presence of olivine, but according to Chelius and Osann this mineral occurs in some of the Odenwald beerbachites (Chelius, 1892, p. 4 ; Rosenbusch-Osann, 1923, p. 323).

Professor Klemm quotes analyses of beerbachite and gabbro-pegmatite, and compares them with analyses of local gabbros. He concludes that the plagioclase of the beerbachite must be thoroughly basic, perhaps bytownite. He also points out that the beerbachite analysis fits well into the series of gabbro analyses, although the percentage of soda is rather high. This analysis will be referred to later on.

Professor Klemm finally concludes that the so-called beerbachites represent the most basic portions of the sediments into which the gabbro was intruded. These portions, owing to their basicity, are supposed to have remained unassimilated by the gabbro, while the more acid sediments suffered extensive resorption and locally modified the composition of the gabbro magma.

In a personal communication Professor Klemm has informed me that he regards the so-called gabbro-porphyrites (Pl. XXII, Fig. 5) as "mix-rocks" of hornfels and gabbro, and thinks that their numerous large plagioclase felspars are not phenocrysts, but crystals derived from the surrounding gabbro.

As we have seen, Professor Klemm has shown that the so-called gabbro-pegmatites are hornfelsed enclosures in the gabbro; he

regards them also as recrystallized sediments or "mix-rocks" of sediment and gabbro.[1]

Professor Klemm supports the sedimentary interpretation of beerbachites by pointing to occurrences, near the margin of the Frankenstein gabbro, of inclusions of sedimentary hornfelses containing corundum, sillimanite, and spinel (Klemm, 1914*a*, pp. 5–9; 1926, p. 115). These had previously been regarded by Kalkowsky as "schlieren" in the gabbro, in which corundum, sillimanite, and spinel had crystallized out owing to local richness in alumina (Kalkowsky, 1914, p. 38).

Professor Klemm has compared the enclosures of corundum hornfels in the Frankenstein gabbro with the corundum hornfelses of Laudenau and Klein Gumpen, also in the Odenwald (Klemm, 1915, pp. 23–41), The latter are associated with other hornfelses containing cordierite, sillimanite, andalusite, garnet, and spinel. Hornfelses similar to those last mentioned are known elsewhere in the Odenwald (Klemm, 1919, pp. 3–32). Professor Klemm considers all these rocks to be metamorphosed sediments, but has recognized the difficulty of accounting for the peculiar chemical composition of the corundum hornfelses (Klemm, 1915, p. 39). He thinks the latter were, before metamorphism, lateritic rocks contaminated by detrital quartz sand and magnesian material derived from the weathering of diabase tuff ("schalstein") (Klemm, 1915, pp. 40–1). These suggestions are of interest in connection with Thomas' views on the origin of the sapphire-xenoliths in the Ardnamurchan gabbro (p. 510).

IV. Discussion and Criticism of the Odenwald Evidence.

The close resemblance between rock-slices of beerbachites and those of the Scottish Tertiary hornfelsed igneous rocks has already been emphasized. A few of the writer's own observations may be added. They refer to a slice of gabbro-porphyrite (Pl. XXII, Fig. 5) and four slices of beerbachite from the Odenwald (Pl. XXII, Figs. 1 and 3), and to the slice of pyroxene-granulite (5369) illustrated by Harker in the Skye Memoir (Pl. XXII, Fig. 2, and Harker, 1904, Fig. 22, p. 115).

Three of the Odenwald beerbachite slices closely resemble the pyroxene-granulite of Skye. The rocks are composed essentially of a mosaic of granules of plagioclase and pyroxene with some iron-ore. A feature common to all the slices, but not mentioned by Klemm or Harker, is a post-granulitization alteration that has resulted in the conversion of some of the pyroxene to green fibrous hornblende. This green hornblende also occurs in veinlets cutting the hornfels mosaic. In one of the Odenwald slices there is a narrow gabbroic vein crossing the section; one of the veinlets filled with

[1] The writer has been unable to examine slices of gabbro-pegmatites, and therefore does not propose to discuss them in detail.

green hornblende crosses the junction between the hornfels and the gabbro vein. The green hornblende of the late cross-cutting veinlet is in continuity with the hornblende that replaces pyroxene both in the hornfels mosaic and in the gabbro vein.

It seems clear, both in the Odenwald and in Skye, that after their consolidation the gabbros, along with their hornfelsed enclosures, were subjected to alteration that produced green hornblende in veinlets and in pseudomorphs after pyroxene. The writer suggests that this later metamorphism is very probably connected with the intrusion of acid plutonic rocks that followed the gabbros both in the Odenwald and in Skye (Klemm, 1910, p. 19 ; Harker, 1904, pp. 5, 83, 121, 122, 139).

The fourth slice of beerbachite from the Odenwald is also largely a typical pyroxene-granulite hornfels with post-granulitization alteration of pyroxene to green hornblende (Pl. XXIII, Fig. 1). The rock is, however, noteworthy for the presence of large irregularly-bounded areas of greenish-brown hornblende enclosing " poikilitically " abundant rounded plagioclase crystals and some iron-ores. This slice was among those sent to the writer by Professor Klemm to illustrate one of the varieties of Odenwald beerbachites. The development of " poikilitic " (or more correctly " poikiloblastic ") hornblende is, of course, well known in hornfelsed igneous rocks (e.g. Teall, 1899, p. 648 ; Bailey, 1916, p. 206). It has been recorded by Thomas in one of the Mull basaltic pyroxene-granulites (Thomas, 1924, p. 155). In this connection we may note that " poikilitic " plates of biotite are found in granulitized basalt lavas in Ardnamurchan (Thomas, 1930*a*, p. 313).

The slice (Pl. XXII, Fig. 5) cut from the gabbro-porphyrite specimen sent by Professor Klemm is of great interest and importance. The rock contains very numerous large tabular crystals of zoned plagioclase ; they are on the whole arranged roughly in parallel, and have other characters of phenocrysts. They show the peculiar grey clouding (due to minute inclusions) that is typical of the porphyritic plagioclase felspars of contact-metamorphosed igneous rocks (MacGregor, 1930, p. 50 ; 1931, p. 524). The " groundmass " of the rock consists essentially of a mosaic of plagioclase felspar, monoclinic and rhombic pyroxene, and iron-ore. Locally the larger felspar laths of the " groundmass ", although very much smaller than the " phenocrysts ", have resisted granulitization except at their edges, and retained their lathy form. The central parts of such relict crystals show the grey clouding typical of contact-metamorphism (cf. MacGregor, 1931, pp. 525, 529). As in the beerbachites mentioned above, green hornblende in the " groundmass " mosaic is in continuity with green hornblende in a veinlet cutting across both the " groundmass " and a plagioclase " phenocryst " (Pl. XXII, Fig. 5) ; in this case the hornblende is solid, not fibrous.

From the general character of the rock, and in particular from the presence of the peculiar clouding *both in the large felspars and in*

"*groundmass*" *felspars that have resisted complete recrystallization*, the writer is convinced that this gabbro-porphyrite is a hornfelsed (granulitized) igneous rock with abundant relict porphyritic felspars. That it is a hornfelsed igneous rock of basaltic (gabbroic) composition is indicated by the similarity of its mineral constitution to that of granulitized basaltic rocks with porphyritic felspars that are common in the Scottish Tertiary gabbro areas (Pl. XXII, Fig. 6). It is, of course, a common feature of granulitized igneous rocks that large plagioclase felspars resist recrystallization although embedded in a granulitized groundmass (Thomas, 1924, p. 154; MacGregor, 1930, pp. 35–8, and 1931, pp. 529, 530).

The writer considers that the evidence of the rock slice, apart from that of chemical analyses of allied rocks (beerbachite and gabbro-pegmatite) invalidates Professor Klemm's hypothesis that this gabbro-porphyrite—a typical example[1]—is a hornfelsed "mix-rock" of sediment and gabbro (p. 512).

The conclusions that Professor Klemm draws from the available analyses of beerbachite and gabbro-pegmatite are somewhat surprising. According to Bastin (Bastin, 1909, p. 472; 1913, p. 195), criteria that help to distinguish an analysis of a sedimentary rock from an analysis of an igneous rock, are the dominance of MgO over CaO, the dominance of K_2O over Na_2O, and the presence of Al_2O_3 in considerable excess of the 1 : 1 ratio necessary to satisfy the K_2O, Na_2O, and CaO. The analyses of beerbachite and of gabbro-pegmatite (V and VIII, Table p. 515) fail to satisfy even one of these criteria. Again, of the numerous analyses of sediments published by Osann (Rosenbusch-Osann, 1923), not one seems even remotely to approach the composition of the analysed beerbachite and gabbro-pegmatite of the Odenwald. Moreover, if the writer has correctly understood Professor Klemm's position, the hornfelsed enclosures of beerbachite in the gabbro are not supposed to have been contaminated by mutual transfer of material from and to the surrounding gabbro.

Basic ashes (tuffs) might, of course, be converted by severe contact-metamorphism into "beerbachites", and such rocks might have analyses like those of basic igneous rocks. It seems to the writer that there is only one kind of deposit that could conceivably be regarded as a "basic sediment", and that on metamorphism might possibly give a pyroxene-granulite with a chemical composition like that of the analysed beerbachite. This would be diabasic or basaltic ash deposited in water, and quite uncontaminated by normal sedimentary detritus. Possibly Professor Klemm has some such deposits in mind when he speaks of "basic sediments".

The gabbro-pegmatite analysis (VIII, Table, p. 515) is very like those of local gabbros (I and III, Table, p. 515). The natural deduction is therefore that the gabbro-pegmatite represents a recrystallized

[1] An excellent illustration of a gabbro-porphyrite has also been published by Rosenbusch-Osann (1923, p. 293).

basic igneous rock of gabbroic composition. The beerbachite analysis is very like that of a local gabbro (III, Table, p. 515), except for a slightly higher percentage of soda. Even if we disregard the possibility of some transfer of soda from the gabbro in which the beerbachite is enclosed, it is not difficult to find analyses of known igneous rocks that agree very closely with that of the beerbachite (Table, p. 515). On the whole perhaps the closest analogy is with an albite-diabase from Devonshire (IV, Table, p. 515).

Analyses of Beerbachite and Gabbro-Pegmatite, and of Igneous Rocks of Similar Composition.

	Gabbro.	Altered Diabase.	Gabbro.	Albite-Diabase.	Beerbachite.	Diabase.	Basalt.	Gabbro-Pegmat.	Luciite Porph.
	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2 .	44·39	45·02	45·94	46·73	47·21	48·41	49·07	49·32	51·70
Al_2O_3 .	18·08	18·42	20·89	18·73	20·52	19·29	19·43	20·22	19·39
Fe_2O_3 .	6·67	4·86	4·30	nt.fd.	7·48	1·33	10·58	4·51	2·54
FeO .	6·90	8·35	4·96	10·14	5·32	8·27	2·35	5·86	6·44
MgO .	6·33	7·19	5·71	3·56	4·16	4·70	4·36	5·63	4·64
CaO .	10·43	8·24	11·77	8·62	8·63	4·93	7·87	10·59	8·95
Na_2O .	1·70	4·67	3·04	3·54	5·17	5·92	3·31	1·63	4·07
K_2O .	0·32	0·38	0·51	0·88	0·33	0·41	0·98	0·34	0·83
H_2O+ .	0·83	2·61	0·68	3·31	0·34	3·99	2·26	—	0·92
H_2O- .	0·00	—	0·00	0·35	0·10	—		—	0·15
CO_2 .	1·00	—	0·91	0·58	0·19	2·41	—	0·04	—
TiO_2 .	1·36	0·94	1·14	2·74	—	0·88	—	1·36	0·14
P_2O_5 .	1·45	—	0·45	0·37	0·46	—	—	0·27	0·37
Rest .	0·28	—	0·12	0·42	—	—	0·32	—	0·48
	99·70	100·68	100·42	99·97	99·91	100·54	100·53	99·77	100·62

nt. fd. = not found.

I. Gabbro. Between Old Eichberg and Kirschberg, Odenwald. Anal. Stadler. Quoted through Klemm, *Notizb. d. Ver. für Erdkunde u. der Hess. Geol. Landesanstalt zu Darmstadt*, V Folge, Heft 9, 1926, p. 113.

II. Altered Diabase. Warmsdorf, Lausitz. Anal. R. Reinisch. Quoted through Washington, U.S. Geol. Surv. Prof. Paper 99, 1917, p. 880.

III. Gabbro. Waldsaum, Odenwald. Anal. G. Butzbach. Quoted through Klemm, op. cit., 1926, p. 113.

IV. Albite-Diabase. Trusham Station Quarry, Devonshire. Anal. E. G. Radley. Quoted from "Geology of the Country around Newton Abbot," *Mem. Geol. Surv. England and Wales*, 1913, p. 62.

V. Beerbachite. Klingeschneise, Frankenstein, Odenwald. Anal. R. Marzahn. Quoted through Klemm, op. cit., 1926, p. 113.

VI. Diabase. Gowganda, Ontario, Canada. Anal. N. L. Bowen. Quoted from Bowen, *Journ. Geol.*, xviii, 1910, p. 667.

VII. Altered Olivine-Basalt. Hailes Castle, East Lothian, Scotland. Anal. J. S. G. Wilson. Quoted through MacGregor, *Trans. Geol. Soc. Glasgow*, xviii, pt. ii, 1928, p. 352.

VIII. Gabbro-Pegmatite. Josephsweg, Frankenstein, Odenwald. Anal. Butzbach. Quoted through Klemm, op. cit., 1926, p. 113.

IX. Lucite Porphyry. Ernsthofen, Odenwald. Anal. W. Sonne. Quoted through Washington, op. cit., 1917, p. 526.

Now we know (Flett, 1913*a*, pp. 60, 63, 71, 72) that such diabases, near granites, are altered to typical hornfelses composed of an equigranular mosaic consisting essentially of hornblende, biotite, and labradorite. Further, we know that similar rocks, when subjected to higher temperature (and possibly other different physico-chemical conditions) associated with the intrusion of diorites and gabbros, are changed partly or completely into pyroxene-granulites[1] (Schwartz, 1924*a*, pp. 135–6); Tilley, 1924*b*, p. 66). In the case of Tilley's researches, on epidiorites in a diorite aureole, the most highly altered rock produced is a granular pyroxene-hypersthene-labradorite-biotite-hornfels, with iron-ores and some relict hornblende. Tilley accounts for the development of diopsidic pyroxene and hypersthene by the splitting up of the hornblende under the highest temperature conditions of the aureole.

There is therefore good reason to believe that the analysed beerbachite represents some kind of basic igneous rock. In this connection we may note that Tilley draws attention to the fact that the hornfels produced from his epidiorite closely approaches the mineral composition of sedimentary hornfelses of Class 6 of Goldschmidt's classification—namely, hypersthene-diopside-plagioclase hornfelses derived from calcareous shale—and that, had the hornblende been completely transformed into pyroxenes, the resemblance would be very striking. He goes on to recall a fact that is very much against a sedimentary interpretation of the Odenwald beerbachites: Chemical analyses of Class 6 sedimentary hornfelses reveal the fact that the quantitative proportions of the various minerals are different from those of igneous hornfelses containing the same mineral assemblage; but nevertheless the mineralogical composition of a reconstituted hornfels is independent of its original mineral

[1] Schwartz (1924*a*, p. 117 and fig. 4) has proposed the term "granoblast" to replace "granulitic gabbro" and "pyroxene-granulite" in describing highly contact-metamorphosed and recrystallized basic igneous rocks. Schwartz's detailed and valuable paper is one of the most important studies of the contact-metamorphism of basic lavas, tuffs, etc., that is known to the writer.

composition. These observations regarding the mineral and chemical composition of reconstructed hornfelses were of course first made by Goldschmidt when he compared his Class 6 sedimentary hornfelses with the hornfelsed essexite-lava of Aarvold (Goldschmidt, 1911, pp. 118, 178).

V. Rosenbusch's Records of Supposed Occurrences of Beerbachite Dykes in Scotland.

At the end of his paper Professor Klemm refers to the supposed occurrence of beerbachite dykes in Great Britain, in the Ural Mountains, and in the United States (Rosenbusch, 1907, p. 638). He says that he has been unable to find out whether these occurrences are in reality dykes or hornfelses (Klemm, 1926, p. 115).

A few notes must now be given regarding the British records to which Rosenbusch refers. In one case Patton appears to have claimed, in a publication which the writer has been unable to obtain (Patton, 1893, p. 184), that a beerbachite dyke occurs in the Scottish island of Rum. Harker in his account of the geology of Rum, based on a detailed survey of the island, makes no reference to Patton; but he mentions the fact that in Rum basic dykes are found entangled, in a highly metamorphosed condition, in the plutonic rock-masses (Harker, 1908, p. 60). If then Patton's supposed beerbachite occurs in situ, there is every reason to believe that it owes its microstructure to contact-metamorphism.

The other record of a beerbachite dyke is also due to a visiting geologist (Busz, 1900, pp. 436–441). The supposed occurrence is near Kilchoan, Ardnamurchan, and the exposure was presumed by Busz to be part of a dyke, although he saw neither of the edges. The locality is in the area that has recently been surveyed in great detail by Mr. J. E. Richey for the Scottish Geological Survey. Mr. Richey tells me that he was unable to detect the exact locality from which Busz collected his specimens, but that he thinks it is highly probable the rock in question was a lava, not a dyke, cut by later granophyre. In any case Busz's "beerbachite" seems identical with igneous rocks (lavas and intrusions) that have been broken through by the Ardnamurchan gabbros, and recrystallized to granulitic hornfelses (*supra*, p. 508). In Mr. Richey's opinion it is quite certain that the beerbachite-like structure of the rock described by Busz is due to contact-metamorphism. No unmetamorphosed rocks of the Ardnamurchan district have such a structure. Moreover, the rock described by Busz had almost certainly been granulitized by a gabbro intrusion before it was invaded by the later granophyre.

Rosenbusch also suggested (Rosenbusch, 1907, p. 638) that Judd's varieties of gabbro with "granulitic structure" must be very like beerbachites. It should be pointed out in this connection that Judd used the term "granulitic structure" with reference to

normal doleritic and basaltic rocks in which the augite occurs as granules, as opposed to ophitic plates (Judd, 1886, pp. 68, 69, 74, 76; and 1885, pp. 360, 361). The structure of the pyroxene-granulite hornfelses discussed above is quite different.[1] This important fact has already been emphasized by Harker (Harker, 1904, p. 52). It is possible, of course, that some of the rocks regarded by Judd as "granulitic gabbros" were in reality hornfelsed igneous rocks.

VI. Conclusions.

The writer believes that the petrological and chemical evidence set out in detail above is overwhelmingly in favour of the igneous origin of the so-called beerbachites, gabbro-porphyrites, and gabbro-pegmatites enclosed as hornfelsed xenolithic masses in the Frankenstein gabbro of the Odenwald. The fact that undoubted sedimentary hornfelses are also found in the Frankenstein gabbro cannot be regarded as affecting the question. This is particularly clear because of the observations of Goldschmidt and Tilley (p. 516) on the mineral composition of reconstructed hornfelses. Moreover, the corundum-hornfels of the Odenwald has its counterpart in the sapphire-rock of Ardnamurchan (p. 510).

The writer would suggest that in the Odenwald one has not to go far to find basic igneous rocks which, if caught up in the Frankenstein gabbro, might be converted into hornfelses like many of the so-called beerbachites and allied rocks. The diabases or the amphibolites that are found in the country-rocks against or near the Frankenstein gabbro (Klemm, 1910, pp. 18, 19; and 1929*a*, "Geologische Übersichtskarte des Odenwaldes") would appear to be the kind of rocks required.

The amphibolites are regarded by Professor Klemm as being very possibly recrystallized diabase-tuffs ("schalsteine"). Both diabases and amphibolites are therefore likely to have a chemical composition approximating to those of the analysed beerbachite and gabbro-pegmatite. It may well be found in the Odenwald, as in Ardnamurchan, that beerbachite-like rocks have resulted from the recrystallization of a number of different basic igneous rock-types. The gabbro-porphyrite, for example, is certainly not a recrystallized tuff.

In view of Professor Klemm's discovery of the real field relations of the beerbachites, gabbro-porphyrites, and gabbro-pegmatites of the type region, the mode of occurrence of supposed beerbachites, etc., in other parts of the world should be reinvestigated. Great care in field and laboratory study is necessary because of the views here put forward by the writer that beerbachites are hornfelsed igneous rocks. For instance, a dyke cutting an older plutonic intrusion may be hornfelsed and granulitized by a later plutonic mass, although the older plutonic rock, owing to its coarser grain,

[1] See footnote, p. 516, for reference to a term proposed by Schwartz to supersede "pyroxene-granulite".

is by no means so obviously affected by the contact-metamorphism (cf. MacGregor, 1930, pp. 38, 46).

It is to be hoped that before many years are past we shall know whether or not there is conclusive field and microscopic evidence to show that any so-called beerbachite (gabbro-aplite) owes its structure to primary magmatic crystallization.

VII. Acknowledgments.

The above conclusions regarding the Odenwald granulites must not be allowed to obscure the great advance made by Professor Klemm in proving that the so-called beerbachites, gabbro-porphyrites, and gabbro-pegmatites are hornfelsed enclosures in the Frankenstein gabbro. Without this first and most important step further progress would have been impossible. It should also be clearly understood that at the time he wrote his paper, Professor Klemm had been unable to read the Scottish Geological Survey Memoirs on Skye, Mull, and Rum; and the Ardnamurchan Memoir had not been published.

Professor Klemm cannot be thanked too warmly for his most generous assistance. Although he knew that the writer's views were to some extent opposed to his own, he not only answered numerous questions in a very cordial personal communication, but at the same time sent literature and rock-specimens to Scotland. Without such generous co-operation this paper could not have been written. It is the writer's hope that the hypothesis here put forward will be confirmed and amplified by Professor Klemm and his fellow-workers in the Odenwald.

Thanks are also due to Sir John Flett for permission to examine rock-slices in the collection of the Geological Survey of Great Britain, and to Dr. H. H. Thomas and Mr. J. E. Richey for their advice regarding the portion of this paper dealing with the Scottish Tertiary granulites. The loan of Odenwald slices from the collections of Edinburgh University has also been of great value. The writer is indebted to Mr. R. M. Craig of that University for his kindness in taking the microphotographs of Plate XXII. The illustration of Plate XXIII is reproduced, by permission of the Controller of H.M. Stationery Office, from a photograph in the official collection of the Geological Survey of Scotland.

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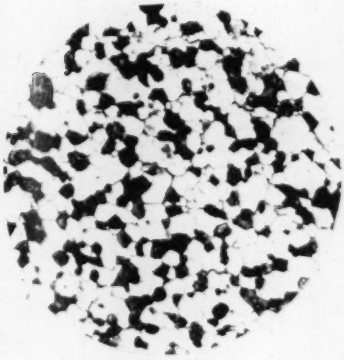


FIG. 1 (× 18).

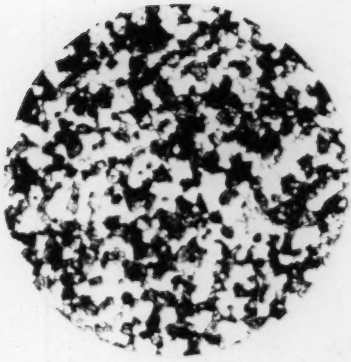


FIG. 2 (× 17½).

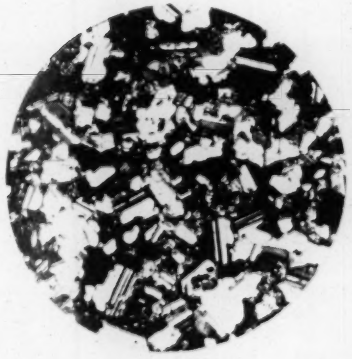


FIG. 3 (× 18).

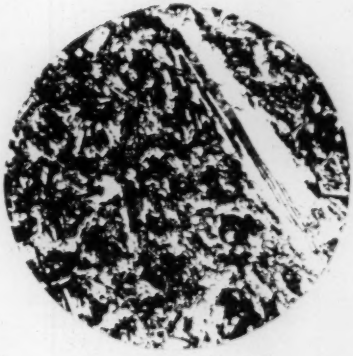


FIG. 4 (× 17½).

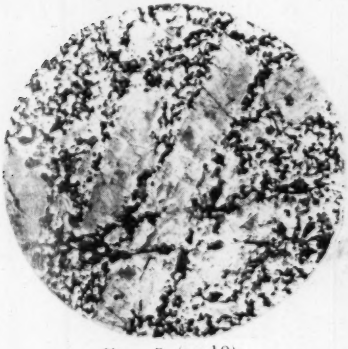


FIG. 5 (× 10).

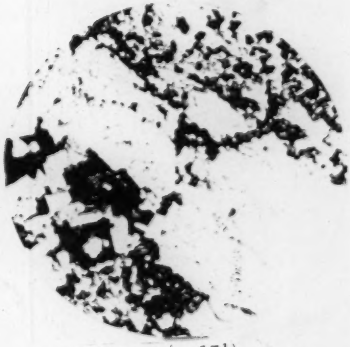
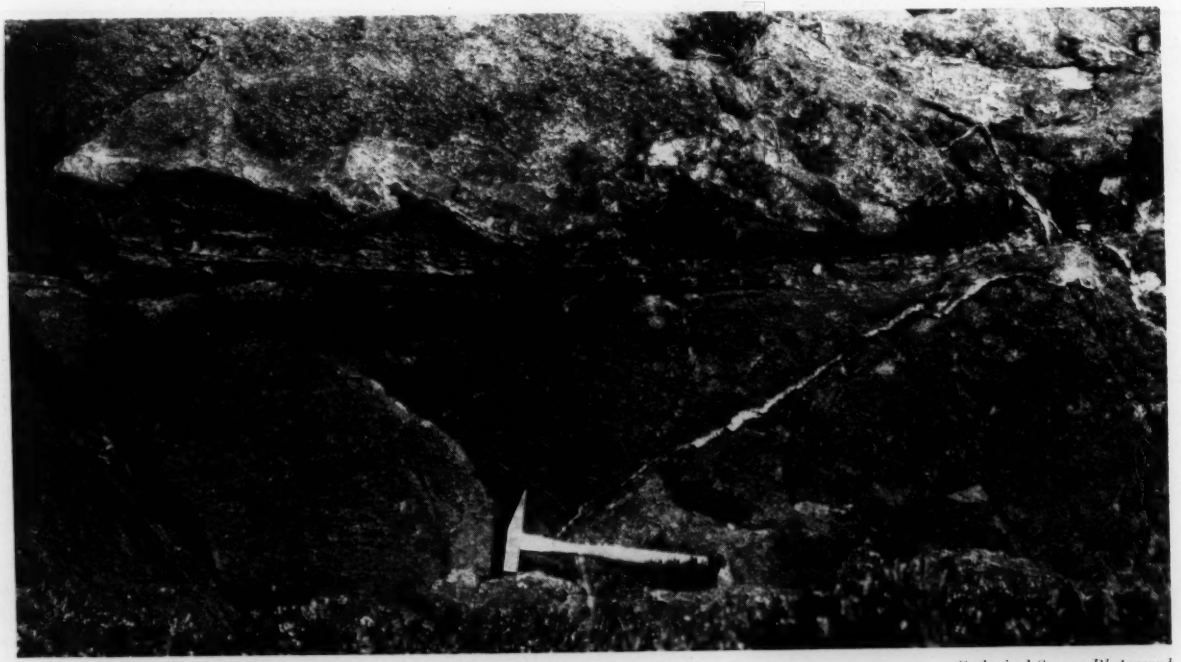


FIG. 6 (× 17½).

PHOTOMICROGRAPHS OF ODENWALD BEERBACHITES, ETC., AND OF GRANULATED SCOTTISH TERTIARY BASALTS.

[*To face p.* 520.



Geological Survey Photograph

Sheet of Granulite Hornfels enclosed in Hypersthene-gabbro, Ardnamurchan.

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EXPLANATION OF PLATES XXII and XXIII.

Plate XXII.

FIG.

1.—Beerbachite. Frankenstein, Odenwald (1,200 metres south of the Castle). Ordinary light. Magnified 18 diameters. Mosaic of plagioclase (white) and pyroxene (grey to dark grey) with some iron-ore granules (black). The pyroxene is largely altered to fibrous green hornblende. A patch of poikiloblastic brown hornblende (2 cm. across) is not included in the photograph.

2.—Granulitized Basalt Lava. Druim an Eidhne, Skye. Ordinary light. Magnified 17½ diameters. Mosaic of plagioclase (white) and pyroxene (grey to very dark grey) with sparse iron-ore granules (black). The pyroxene is partly altered to fibrous green hornblende.

3.—Beerbachite. Frankenstein, Odenwald (just north-west of Castle ruins). Crossed nicols. Magnified 18 diameters. Allotriomorphic aggregate of plagioclase (twinned), and pyroxene largely replaced by fibrous green hornblende (grey to dark grey), with irregular patches of iron-ore (black).

4.—Contact-Metamorphosed Basalt Lava. South-west side of Meall an Tarmachain, Ardnamurchan (10 yards from gabbro). Crossed nicols. Magnified 17½ diameters. A small relict plagioclase phenocryst is clearly seen. In the groundmass the original plexus of diversely arranged plagioclase laths is scarcely recognizable owing to recrystallization which has involved the formation of pyroxene granules. Many of these are rendered almost black by included iron-ore dust. Note the scalloped edges of the small phenocryst and of relict groundmass felspars.

5.—Gabbro-Porphyrite. Frankenstein, Odenwald. Ordinary light. Magnified 10 diameters. The relict plagioclase phenocrysts, with scalloped edges and clouding typical of contact-metamorphism, are clearly seen. The groundmass has been recrystallized to a granulitic aggregate of plagioclase, rhombic and monoclinic pyroxene, and some iron-ore. Near the bottom of the photograph a post-granulitization hornblende veinlet cuts across the groundmass and the large phenocryst.

6.—Granulitized Porphyritic Basalt. Beinn Ghlas, Ardnamurchan. Ordinary light. Magnified 17½ diameters. Around the relict plagioclase phenocrysts the groundmass is largely recrystallized to a granulitic aggregate of plagioclase and rhombic and monoclinic pyroxene, with some iron-ore.

Plate XXIII.

Sheet of granulite hornfels enclosed in hypersthene-gabbro. The banded upper margin of the granulite is irregularly invaded by the gabbro. Aplite veins cut both gabbro and granulite. The locality is south-west of Beinn na Seilg, Ardnamurchan.

REVIEWS.

VOLCANOES. By G. W. TYRRELL. No. 151 in the Home University Library. pp. 252. London: Thornton Butterworth, 1931. Price 2*s*. 6*d*. net.

OF the various branches of petrological study, volcanology lends itself most readily to popular exposition. In a book written for the general reader as well as for the student, Dr. Tyrrell makes wise use of this approach. From a consideration of the products of volcanism and the phenomena of eruption, one is gradually led backwards in time from Hawaii and Etna, through stages of decadence to ancient volcanoes and a study of igneous activity in general. By the time the last chapter is reached, the reader has been adequately prepared to assimilate an outline of the theories of geological cycles and the generation of magmas. A bibliography maps out a suggestive and comprehensive course for further reading.

F. C. P.

GRUNDPROBLEME DER GEOLOGIE, eine Einführung in geologisches Denken. By SERGE VON BUBNOFF. pp. viii + 237, with 48 text-figures. Berlin: Borntraeger, 1931. Price 11·60 R.M.

THE writer of this small book is already well-known as the author of that vast work, now in course of publication, *Geologie von Europa*. The first volume of this was reviewed in December, 1926; the first part of the second volume has just come to hand. The object of the present work is, as stated in the title, to serve as an introduction to geological thought. So far the subject does not seem to have been tackled at all from a philosophical standpoint. The first chapter, on the epistemological basis of geology, is extraordinarily interesting and stimulating; it is only too short (13 pages). The greater part of the book is taken up with a statement of some of the hitherto unsolved fundamental problems of the science, an account of prevailing theories, and acute criticism of their merits and defects. There is a discussion of the present state of our knowledge of sedimentation, and of the petrology of the igneous and metamorphic rocks. But the author's strongest bias is towards earth-movements and mountain-building from the physical and historical standpoints. He discusses at some length the work of such writers as Kober and Stille, the various schools of alpinists, Gutenberg, Goldschmidt and Holmes, as well as the exponents and opponents of continental drift. Stable blocks, shelfs and geosynclinals are dealt with, as well as recent ideas on continents and ocean basins, isostasy and gravity anomalies, and in fact all the broader topics of recent geological speculation.

Dr. von Bubnoff does not seem to have much sympathy with land-bridges, and on the whole, though without any dogmatism, he thinks that mobile continents agree with the facts better than any kind of fixity.

In the chapter on earth-movements in time and space it is somewhat alarming to find that the original three major revolutions, Caledonian, Armorican and Alpine, have now been increased by the Stille school to thirty-two. All this seems to indicate a certain lack of a sense of proportion. Some of these disturbances are undoubtedly very local and of small importance, and little attention is paid to the possibility that such may take a considerable time to travel from one area to another. For example, the older Cimmerian phase in S.E. Europe (Dobrudsha and Crimea) is somewhere about the Rhaetic; the younger Cimmerian in Hanover and England is of Portlandian age. May not these uplifts be really manifestations of one and the same process?

This excellent book may be strongly recommended to English-speaking readers who desire to obtain an idea of the general trend of geological thought in Europe. Indeed it is much to be wished that it might be translated into English by a competent geologist, as such a translation could not fail to be useful to that numerous class who find German reading somewhat heavy going. In default of this, we would say that the perusal of this work, even with a dictionary, might be labour well spent.

THE AGE OF THE EARTH. Bulletin of the National Research Council. pp. 487. Washington, D.C., 1931.

EVERY geologist must be weary of being catechized about the age of the earth; no question is more often asked by non-geologists and none has hitherto been more impossible to answer except by a confession of complete ignorance. Until quite recent times all estimates have turned out to be based on incorrect or incomplete data, like the famous one of Lord Kelvin, which led to an impossibly short period that no physical geologist or biological evolutionist could accept. The calculations based on the saltness of the sea were altogether too vague, besides ignoring the possibility, or indeed probability, of an original chlorine content from condensation of the early atmosphere—also it is now obvious that estimates of the rate of denudation throughout geological time are quite unreliable, while for sedimentation the data are little better, and it is practically impossible to determine the time-value of stratigraphical discontinuities. At last, however, it seems probable that the later developments of atomic physics may give us some safe basis for the construction of a time scale since, at any rate so far as we know at present, the rate of radioactive disintegration of certain elements is absolutely unaffected by any change in the physical environment that is conceivable since the

earth acquired a solid crust. Therefore since the actual present rate of such changes can be measured with great accuracy it is legitimate to extrapolate such physical constants back into remote ages.

The book under review is an attempt to apply the results of such physical investigations to the concrete problem of the age of the earth as a whole and of the subdivisions of the rocks composing the accessible portions of its crust.

It consists of six sections: A Summary of Principal Results, by A. Knopf; Geochronology, or the Age of the Earth on the Basis of Sediments and Life, by C. Schuchert; Age of the Ocean, by A. Knopf; Calculating the Age of Minerals from Radioactive Data and Principles, by A F. Kovarik; Radioactivity and Geological Time, by Arthur Holmes; The Age of the Earth from Astronomical Data, by E. W. Brown. Of these sections, that by Professor Holmes is by far the longest, covering some 330 pages, or two-thirds of the book. In this review attention will be mainly confined to it.

Professor Holmes here treats very fully indeed all the available data bearing on his subject, and he has collected an enormous bibliography. The greater part of the text consists of an elaborate discussion of the principles of radioactive disintegration, with special attention, as is natural, to uranium-lead and thorium-lead ratios, which form the most important basis on which estimates of the absolute ages of minerals and rocks are founded. The details are of course of less interest to geologists than the results to which they have led, and in all this mass of material it is not altogether easy to pick out the most salient points. What the geologist wants is an absolute time scale, and it appears that an approximation to the evaluation in years of the date of certain geological formations can now be made. It seems highly probable that the Tertiary began about sixty million years ago; that late Carboniferous rocks are about 250 million years old, and the Pre-Cambrian includes the date 1000×10^6. (This date bears a suspicious resemblance to 1066 and all that.) The highest lead-uranium ratio hitherto found in a mineral is 0·216 in the uraninite of the Black Hills in South Dakota, which is calculated to correspond to an age of 1,460 million years. All these ancient minerals, however, occur in rocks intrusive into something older, possibly much older, so that they afford only minimum values for the age of the earth's crust. A point of some interest is noted on p. 356, namely, that the leading concentrations of strongly radioactive minerals during Pre-Cambrian times occurred definitely earlier in Laurasia than in Gondwanaland.

From the study of helium ratios also some interesting results have been obtained. Thus it is calculated that the age of the Cleveland Dyke is 28×10^6 years, that of the Deccan traps 37×10^6, and of the Whin Sill 196×10^6 years. The last agrees quite

reasonably well with the figure of 250 million years otherwise obtained for the Carboniferous, since the limit of error in such delicate determinations must necessarily be wide.

It seems fairly obvious that estimates of the age of the ocean, based on sodium content, and of the age of stratified formations from rates of denudation and deposition are quite unreliable. Professor Schuchert finds himself obliged to check his geological results by calling in the data of radioactivity. Finally, in the last section of the book Professor E. W. Brown starts off with the frank confession, "There are no known methods derived from astronomical data alone for estimating the age of the Earth." We are therefore forced to the conclusion that at the present time the physics of radioactive disintegration of the elements, difficult and uncertain as they are, afford the best approximation to a geological time-scale.

THE STUDY OF ROCKS. By S. J. SHAND. pp. xi + 224. London: Thomas Murby and Co., 1931. Price 6*s*. net.

PROFESSOR SHAND has not merely added one more conventional introductory text-book to our libraries. Not only students would benefit greatly by a careful perusal of this introduction, but many more advanced petrological workers also, who will find interest and food for thought in its helpfully critical outlook. Chapters dealing with the field occurrence and the chemistry of eruptive rocks are followed by a stimulating discussion of their classification, wherein each author of a classic text-book is uncompromisingly confronted with the number of different rock-names which he employs. The detailed descriptions of these rocks follow, on the lines to be expected from the author of *Eruptive Rocks*; and the remaining chapters cover sediments and the products of metamorphism. Here the author's passion for simplified nomenclature sometimes leads him further than we should be prepared to follow; is it wise, for example, to allow a student to suppose that "hornstone" is the accepted English equivalent of "hornfels"? Each chapter concludes with a *few* well-chosen suggestions for further reading; and in a laudable attempt to interest the student in chemical work a three-page appendix outlines the successive steps in the analysis of a silicate rock. Throughout, the book lives up to the promise of its opening sentence—"The study of rocks should be begun in the field, carried on under the microscope, and finished in the crucible."

F. C. P.

CORRESPONDENCE.

THE HEAVY MINERAL CORRELATION OF IGNEOUS ROCKS.

SIR,—I have just seen the June issue of the GEOLOGICAL MAGAZINE, in which Dr. A. K. Wells has reviewed and criticized on theoretical grounds the heavy mineral correlation of intrusive igneous rocks as introduced and advocated by me in three papers in this Magazine. In his joint paper with Dr. S. W. Wooldridge on the rock groups of Jersey further criticisms are made. I welcome Dr. Wells' presentation of the theoretical objections to the method, though they are somewhat vitiated by his lack of an equally thorough appreciation of the practical side.

First, however, there are some points which do me injustice. The fact that I have changed the age I assign to the Jersey "Newer" granites appears to have given Dr. Wells special grounds for viewing the evidence of the accessory minerals with suspicion. The facts are these: Having convinced myself that there are two ages of granites in Jersey, I secured some specimens of acid plutonic intrusions in Alderney, which I correlated with the "Newer" granites of Jersey. Now, as the intrusions in Alderney had been shown by Dr. Plymen to be unconformably overlain by early Cambrian sediments, the "Newer" granites were considered to be Pre-Cambrian. This was the only stratigraphical evidence available, as I have already been informed of the disproof by Drs. Wells and Wooldridge of Dr. Plymen's evidence at Gorey, and in the interval between this and my 1930 paper in this Magazine Mr. Mourant had found the Alderney contact, in part at least, to be a thrust plane, and in any case to be remote from the granite in question. At the same time I had extended my work to the granites of the neighbouring parts of Normandy and Brittany. The heavy mineral assemblages showed that the Jersey "Newer" granites were to be correlated with the granites, presumably on the same fold axes, of Flamanville and Trégastel, which stratigraphical evidence shows to be later than Lower Devonian and very probably Post-Dinantian. As Dr. Wells observes, the Jersey granites still yield the same heavy mineral suites as in 1927, but apparently he fails to appreciate that it is the stratigraphical links which have changed at the hands of other workers and partly as the result of the extension of my own work to Normandy and Brittany.

I agree with Dr. Wells regarding the importance of the examination of thin sections, which should go hand in hand with heavy mineral correlation. My work in Africa shows that the "Newer" or G.2 granites of Uganda and neighbouring territories—over an area of several thousand square miles—are very nearly uniform both in thin section and heavy mineral suites.

Comparing rocks similar in all other respects, Dr. Wells states

that identity of mineral composition can only occur if the rock bodies have had the same cooling history. He is, however, considering the cooling history of the rock right up to its closing stages, whereas it is a well-known fact that the primary stable accessory minerals begin to crystallize before the major constituents. This may readily be proved in artificial melts, while the converse, the stability of these minerals when caught up by a granite magma, was demonstrated by the writer in the Channel Islands and later by Dr. A. Fitch in the Dartmoor granite. It would appear that these minerals, which are of paramount importance for correlation purposes, have a fair chance of crystallizing before such disturbing effects as the rate of cooling in the later part of the cooling history, or the contamination of the magma by assimilation, can very materially affect them. I would therefore expect the minerals classed as normal accessories by Dr. Wells to be less affected by the size of the intrusion, manner of injection, thickness of roof, etc., than the major constituents seen in thin sections.

Dr. Wells considers that pneumatolytic minerals are confined to the upper part of an intrusion and are " without value as indicators of age ". Admittedly they are usually a late product, though not without exception, as Brammall has shown. Usually, also, they are confined to the top of an intrusion, but the " Newer " granites of Central Africa are throughout characterized by the same pneumatolytic minerals though all the evidence points to their very deep erosion. For example, out of 41 specimens crushed from 20 different masses of the " Newer " granites of Kenya, Uganda and Tanganyika, 31 yield some or all of the minerals tourmaline, cassiterite, anatase, brookite, fluor, topaz, and pyrite.

Dr. Brammall and others have shown that the Armorican granites of Devon and Cornwall possess one distinctive pneumatolytic mineral suite. In the almost complete absence of beryllium minerals these Armorican granites and those of the Channel Islands, Normandy and Brittany contrast strongly with the Tertiary granites of the Mourne Mountains. While pneumatolytic minerals are second in importance to the primary accessories, Dr. Wells' sweeping generalization is quite unjustified.

It is incomprehensible to Dr. Wells that " generic " features should distinguish British Armorican granites from the Pre-Cambrian, Caledonian and Tertiary masses while at the same time more specialized characters should permit distinction between the heavy mineral assemblages of single intrusions. Brammall, Leech, Ghosh and Chatterjee have surely amply proved this, but Dr. Wells will doubtless continue sceptical until his obvious distrust of heavy minerals is overcome by weight of experimental evidence or by personal application to the practical side of the work.

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